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INTERIM REPORT

TASK MSC/STL A-17

LUNAR SURFACE ACCESSIBILITY CONTOURS—ACTION ITEM NUMBER ONE (U)

12 MAY 1965

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THOMPSON RAMO WOOLDRIDGE INC.

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INTERIM REPORT

TASK MSC/STL A-17

LUNAR SURFACE ACCESSIBILITY CONTOURS—ACTION ITEM NUMBER ONE (U)

12 MAY 1965

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ABSTRACT

This interim report is submitted to MSC in partial fulfillment of Task MSC/STL A-17 of the Mission Trajectory Control Program, Phase II, Contract NAS 9-2938. It contains the results of Apollo Spacecraft performance under the ground rules specified in Action Item Number One, appended to the original task. This analysis is presented in terms of lunar landing site accessibility for contours of LEM plane change capability and Service Module velocity capability. This analysis has also been conducted for fixed spacecraft weights during an entire lunar month with the results presented as contours of minimum Service Module propellant and deboost and transearth injection velocity.

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1. INTRODUCTION

Further evaluation of lunar landing site accessibility for modified ground rules was conducted by TRW Space Technology Laboratories as a part of Task MSC/STL A-17 of the Mission Trajectory Control Program, Phase II, Contract NAS 9-2938 (Reference 1). This additional analysis was requested in an Action Item (Reference 2) drawn on 9 March 1965 and appended to the Task Implementation Plan (Reference 3).

A preliminary disclosure of results was made to the NASA Manned Spacecraft Center on 9 and 10 April 1965. This document reports the analysis conducted under Action Item Number One and is submitted in accordance with the conditions specified therein.

This report contains the results of the analyses of lunar landing site accessibility for the revised ground rules. These results are presented in terms of lunar landing site accessibility and Service Module (SM) ΔV requirements (both at translunar deboost and transearth injection). The objectives of this study are three fold:

1) To provide lunar area accessibility contours for the limiting launch dates in February 1970 and one LEM configuration.

2) To generate the ΔV contours associated with the limiting launch dates.

3) To generate ΔV contours and SM propellant contours for every day in February for the prime Apollo landing area defined by $\pm 45^{\circ}$ longitude and $\pm 5^{\circ}$ latitude. These are for a fixed LEM weight and optimized for minimum SM propellant.

Section 2 contains a general discussion of the technical approach and the ground rules applied to this study. The analysis is discussed in Section 3, and the results and conclusions are summarized in Section 4.

2. DESCRIPTION

The technical approach used in this analysis has been described previously in work reported under Task A-15 (Reference 4) and Task A-17 (Reference 5). This approach was used in generating the contours presented in Sections 3. 1 and 3. 2, which allows the off-loading of SM propellant in exchange for LEM propellant depending on the LEM ascent plane change required. This approach maximizes lunar landing site accessibility for each LEM configuration (plane change capability) and set of mission parameters listed in Table 1. The calculations were performed with calibrated analytic computer programs. Input data consists of the Saturn V payload/injection velocity relationship determined in a subtask to Task MSC/STL A-15, and the spacecraft weights and LEM ascent performance capability specified in the A-17 Task Assignment (Reference 1).

Once the lunar landing site contours are determined for the days which limit site accessibility, the composite of all such contours can be drawn for a lunar month which will define the 100 percent accessibility area. This is the objective of the first part of this report.

The velocity increments demanded of the SM in executing the maneuvers necessary to achieve this 100 percent accessibility can also be shown as contours on the landing site region. This analysis requires no special technique, the necessary information is merely fallout from the data required for the landing site contours (depicting LEM plane change). These contours are presented in the second part of the report.

The approach required in the third phase of this study resulted in some logic modifications to the Lunar Operations Program (LOP) computer program. This phase of the study required minimum SM propellant expenditure with a fixed spacecraft weight (CSM inert and LEM weight are fixed but the spacecraft is otherwise loaded to injection capability on each day). The logic in this case requires choosing the minimum propellant weight within the allowable azimuths of those orbits passing over the site. These azimuths are bound by the LEM plane change capability and the spacecraft injected payload on any given day. Consequently, this procedure is opposite to the previous technique

Table 1. Ground Rules

	Parameter	Limits
1.	Length of mission	optimum
2.	Maximum translunar flight time	95 hr
3.	Maximum transearth flight time	110 hr
4.	Approach conic pericynthion	80 nmi
5.	Lunar parking orbit altitude	80 nmi
6.	Number of orbits before CSM/LEM separation	2
7.	Landing site region (sufficient latitude range)	$\pm 45^{\circ}$ in longitude
8.	Lunar surface stay time	36.6 hr
9.	Number of orbits between docking and transearth injection	2
10.	Departure conic pericynthion	free
11.	Return inclination	$\pm 40^{\circ}$
12.	Reentry maneuver range	2000 nmi
13.	Earth landing site	Hawaii or Samoa
14.	Nominal CSM weight	21,200 lb
15.	SM specific impulse	313 sec
16.	Translunar midcourse	370 ft/sec
17.	Transearth midcourse and contingency	815 ft/sec

of minimizing LEM plane change at a particular site, for here, in many cases, the LEM must take its maximum plane change in order to minimize SM propellant required. In this case, as in the previous case, results can be given as contours of SM propellant (equivalent to LEM weight for a fully loaded spacecraft) and the velocity increments at deboost and transearth injection. This approach determines the minimum performance expected of the SM on any day. There would, in actuality, be some balance between SM propellant reserve and LEM propellant reserve at each of the sites. This trade-off is also illustrated.

3. ANALYSIS

3.1 LUNAR AREA ACCESSIBILITY CONTOURS

The lunar area accessible with the decreased translunar flight time has been reduced to about 5/6 of the previously accessible area as shown in Figure 1. This effect not only reduces the area accessible for a given LEM plane change capability, but also results in the SM limit being reached in two of the four quadrants. The SM limit bounds the region where SM propellant can no longer be exchanged for the LEM propellant used to accomplish the greater LEM ascent plane changes. The area above these limits is not accessible for the given spacecraft payload capability on that limiting day.

Each quadrant of the landing area in Figure 1 has the limiting launch date indicated along with the translunar (TF1) and the transearth (TF2) flight time and the total spacecraft lunar injected weight (W_{INJ}). Table 2 tabulates the differences between the limiting dates which were found with the constraints in the original Task MSC/STL A-17 and those found to be limiting with the new constraints that were listed in Table 1. The limiting launch days have shifted in three of the four quadrants. In the western landing area the launch day moved ahead by one in Quadrant 2, which coupled with the shorter translunar flight time arrived at the moon only 10 hours later than the previously analyzed 11-day mission. In Quadrants 1 and 4 in the eastern landing area, the limiting days moved back by 2 days. This may be expected since the 10- and 11-day missions were considered to be launched on the same day in the previous analysis, and as a consequence, the 10-day mission did not provide the minimum accessibility. However, these limiting days are limiting only by very scant margins, as 2, 3, and sometimes 4 days near this launch date exhibit very much the same accessibility.

For the constraints now considered, three of the quadrants show a 10-day mission providing the maximum accessibility, and the last quadrant providing maximum accessibility for a 10-1/2-day mission. From an operational viewpoint the shorter mission (10 versus 11) is superior and it provides an unexpected bonus of greater site accessibility. This data was generated

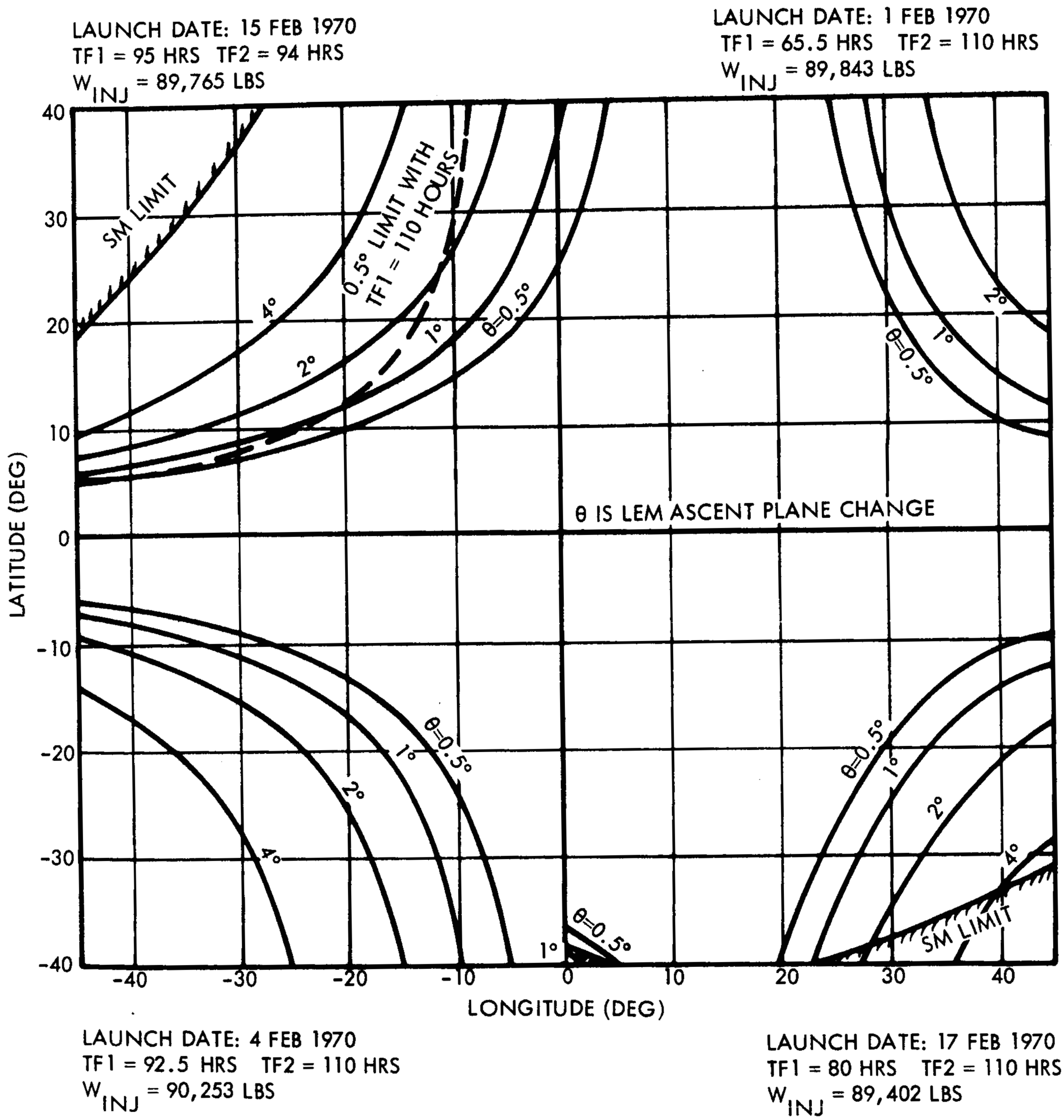

Figure 1. 100 Percent Lunar Site Accessibility for February 1970
LEM Configuration ≅ 32,000 lb at 2° Plane Change

Table 2. Lunar Landing Accessibility Contours
Comparison with Previous Data

Landing Site Quadrant	Launch Date		TF1		TF2	
	Old	New	Old	New	Old	New
1	3 Feb	1 Feb	67.5	65.5	110	110
2	14 Feb*	15 Feb	110	95	103	94
3	4 Feb*	4 Feb*	110	92.5	93	110
4	19 Feb	17 Feb	83	80	110	110

*Nominally defined as an 11-day mission, others are defined as 10-day missions.

with a variable LEM weight which was a function of the plane change required. The weight is shown in Table 3. The actual limiting accessibility limit for a 32,000-pound LEM corresponds to the 2^{o} line in each quadrant. This limit utilizes all of the propellant in the LEM and executes the full 2^{o} plane change. The SM is fueled to the spacecraft injected weight limit on each launch day and all of its propellant is used in the required lunar operations and midcourse corrections. Thus, this 2^{o} line represents the maximum achievable landing site latitude at that longitude. Sites within the area of Apollo landing box ($\pm 45^{o}$ longitude and $\pm 5^{o}$ latitude) are always accessible during the month for these nonfree return trajectories.

The next four figures (Figures 2 through 5) are contours on the full landing area for each of the limiting days. The combination of flight times chosen on a particular day is optimum only for the limiting quadrant. Other flight time combinations would be chosen for the other quadrants. In fact, the flight time combination would be optimized for each site to provide minimum LEM plane change or SM propellant expended or some combination of the two, to maximize the propellant reserve in each case. This propellant reserve will be discussed further in Section 3. 3.

Figure 2 shows the contour for the limiting launch day in Quadrant 1 which is 1 February 1970. The accessible area is quite large considering the translunar time of flight is only 65. 5 hours. Both Quadrants 1 and 4 reflect the philosophy of chosing the longest possible transearth flight time for landing sites in the eastern hemisphere. And conversly, the short translunar flight time has a negative effect on the western landing area. Here, the longest possible translunar flight time would be chosen to maximize accessibility. The minimum SM propellant/LEM plane change region appears to be skewed from Quadrants 2 to 4. This is due to the libration of the moon at this particular time. The translunar trajectory v-infinity asymptote is in the earth-moon plane in Quadrant 2 at about 6^{o} latitude and -53^{o} longitude. Whereas, the transearth v-infinity asymptote is in Quadrant 4 at from -3^{o} to -14^{o} latitude (depending on the return inclination of the transearth trajectory), and at 88^{o} longitude. A latitude of -5.5^{o} at 88^{o} longitude is in the earth-moon plane at

LIMITING DAY FOR QUADRANT 1
32,000-LB LEM (AT 2° PLANE CHANGE)
TF1 = 65.5 HOURS TF2 = 110 HOURS
W_{INJ} = 89,843 POUNDS

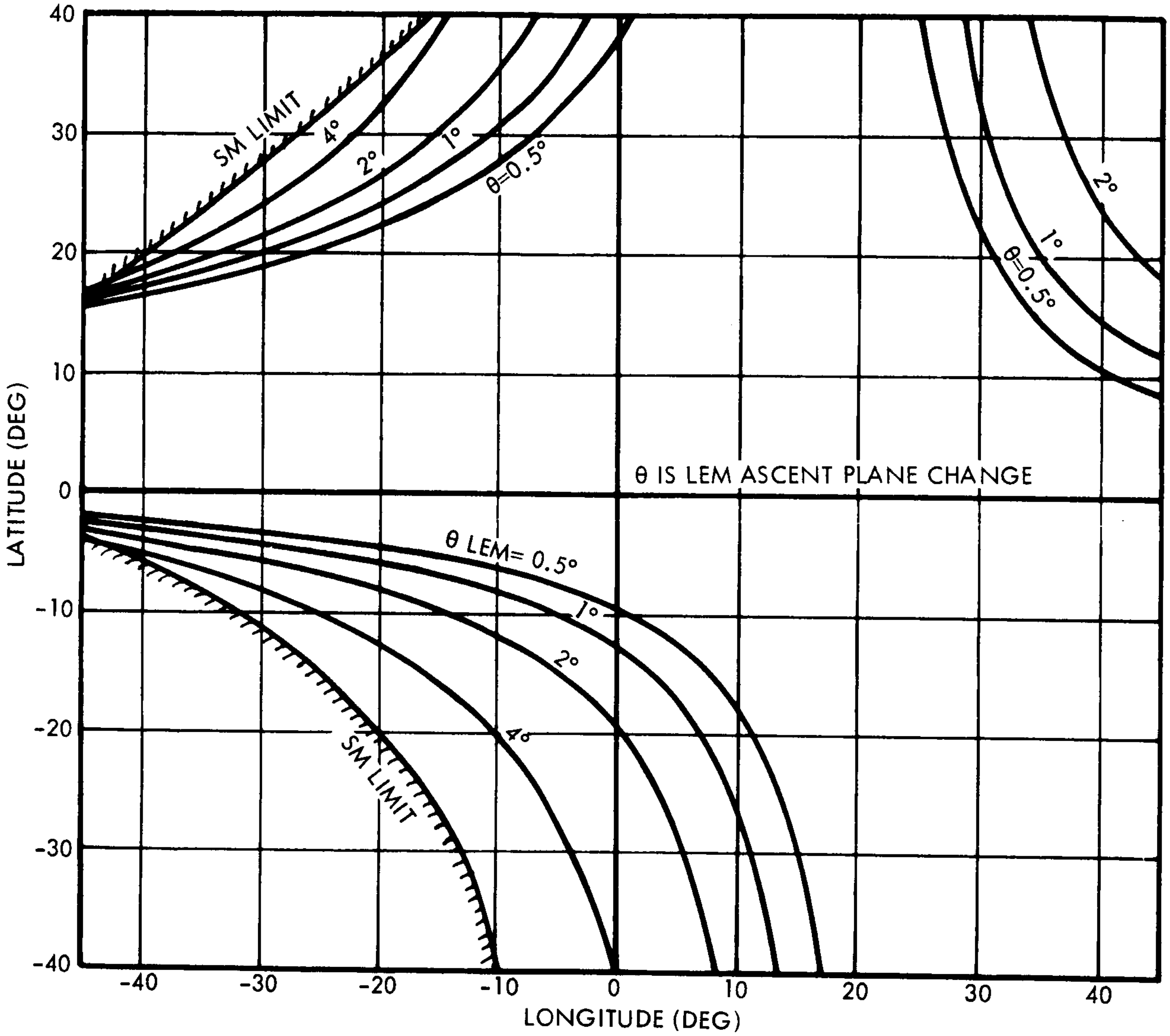

Figure 2. Lunar Surface Accessibility for 1 February 1970

LIMITING DAY FOR QUADRANT 3
32,000 LB LEM (2° PLANE CHANGE)

TF1 = 92.5 HOURS TF2 = 110 HOURS
W_{INJ} = 90,253 POUNDS

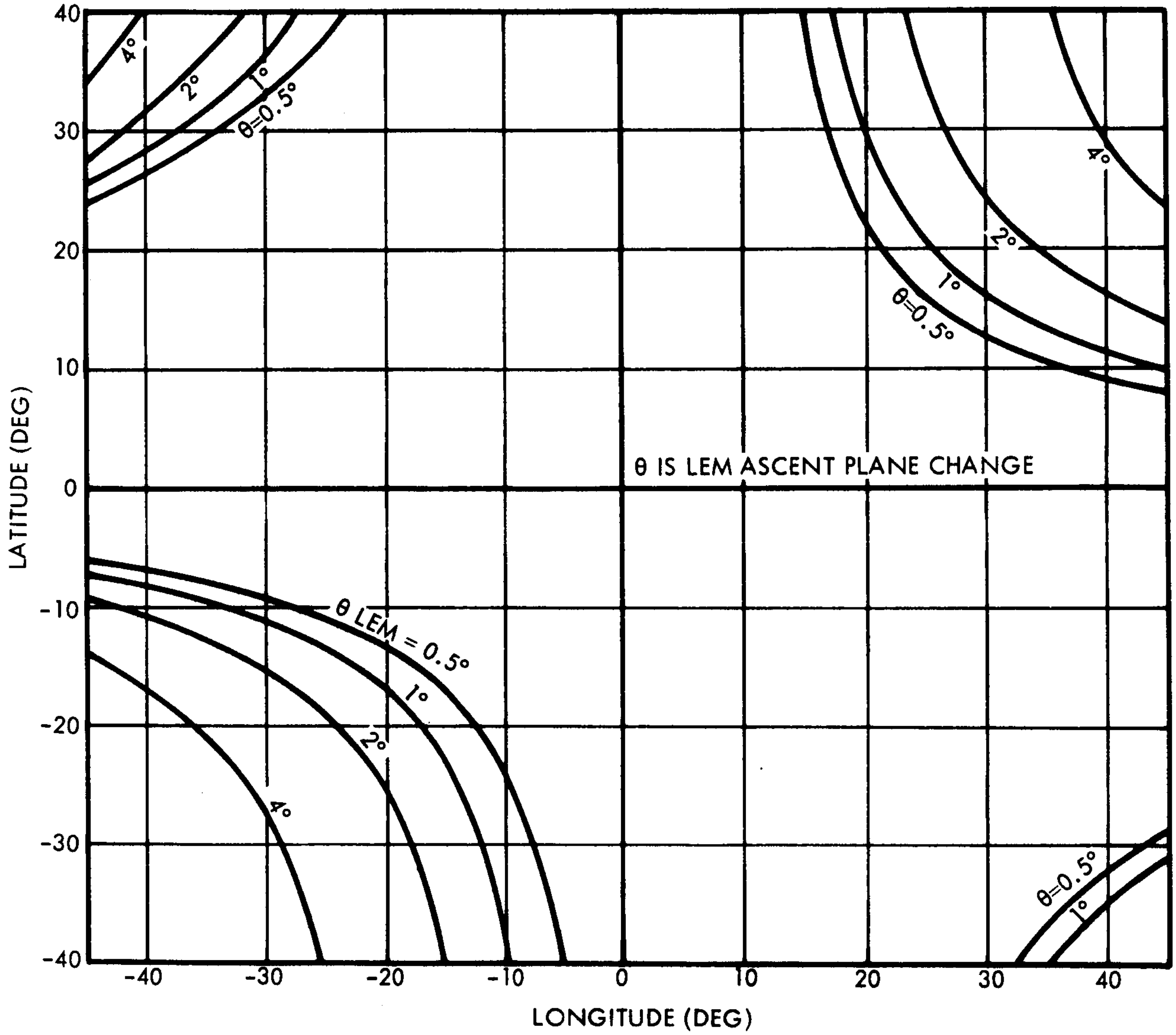

Figure 3. Lunar Surface Accessibility for 15 February 1970

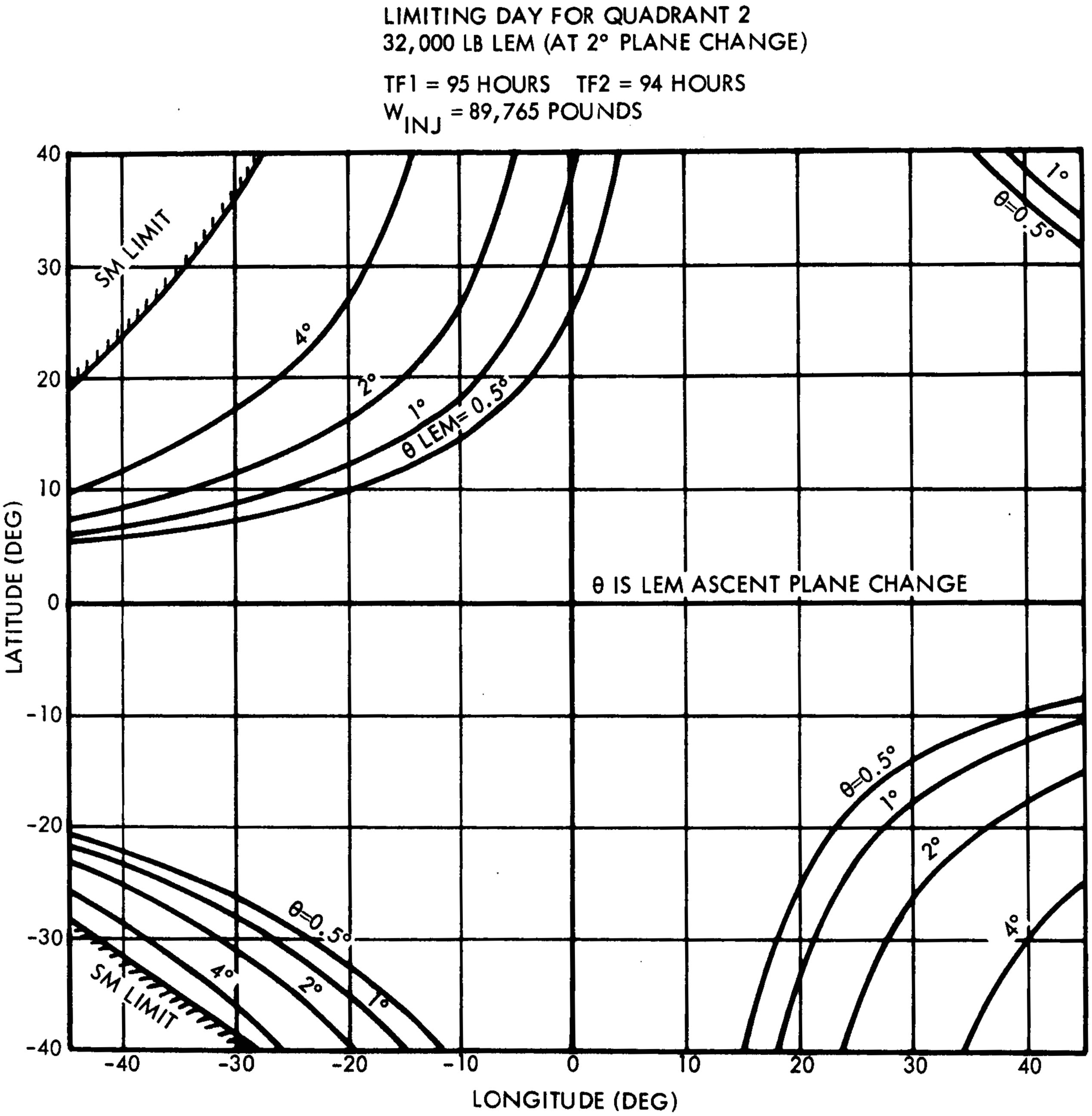

Figure 4. Lunar Surface Accessibility for 4 February 1970

LIMITING DAY FOR QUADRANT 4
32,000 LB LEM (2° PLANE CHANGE)
TF1 = 80 HOURS TF2 = 110 HOURS
W_{INJ} = 89,402 POUNDS

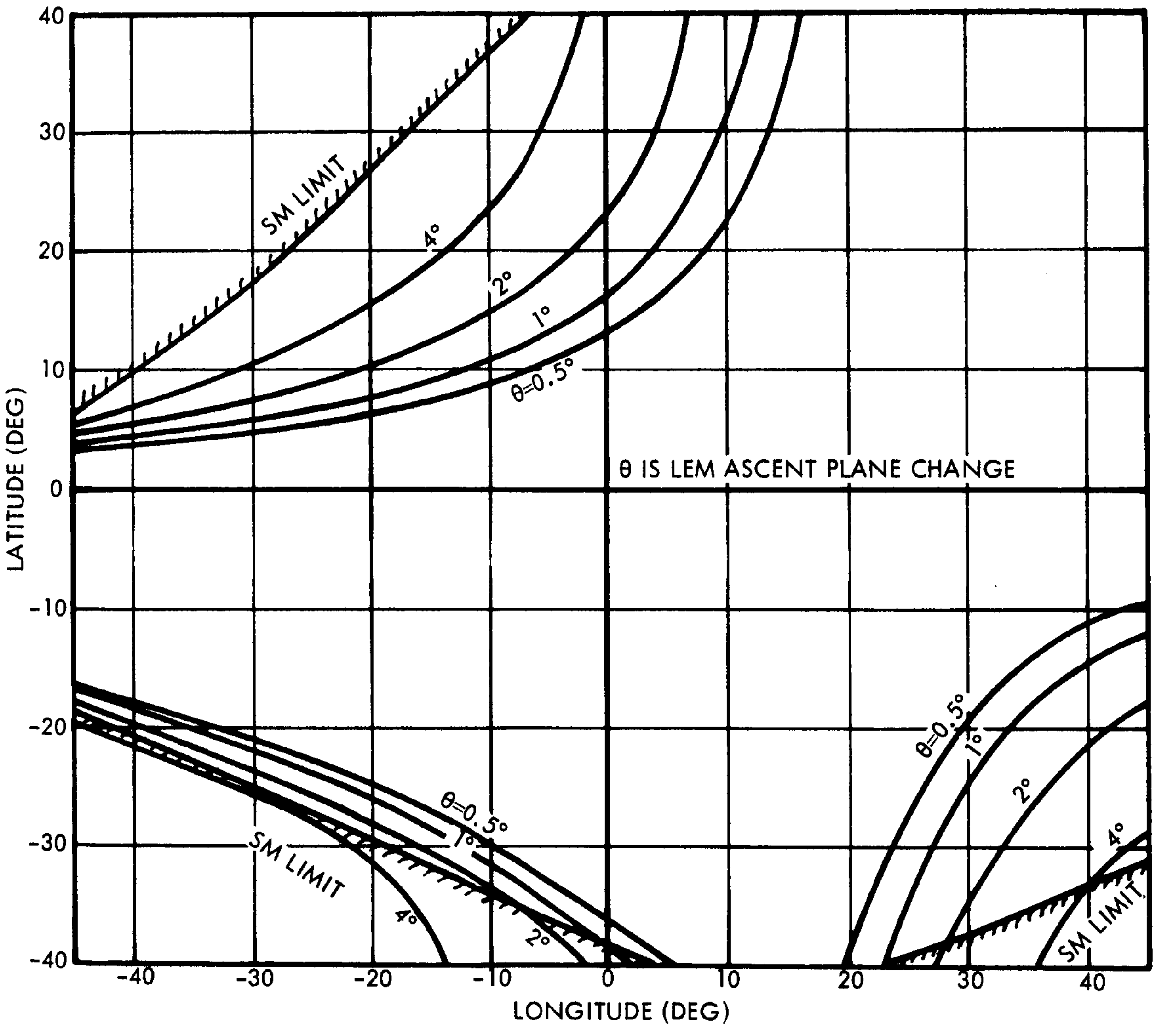

Figure 5. Lunar Surface Accessibility for 17 February 1970

Table 3. LEM Weights*

LEM Plane Change (deg)	LEM Weight Without Men (lb)
0.5°	31,654
1.0°	31,769
2.0°	32,000
3.0°	32,231
4.0°	32,462

*These weights are used in the analysis in Sections 3.1 and 3.2. In Section 3.3 the LEM has a fixed weight of 32,000 pounds with a 2° plane change capability.

transearth injection. The minimum SM propellant would occur for an in-plane deboost and in-plane transearth injection. This would place the minimum propellant contour near the trace of the earth-moon plane on the surface of the moon with some flexibility at the western end, due to the freedom in optimizing the return inclination of the transearth trajectory. The moon's rotation would move the apparent position of the transearth asymptote by another 30° during the lunar stay. The apparent difference of the two asymptotes would then be the sum of the longitudes of the asymptotes and the rotational movement or a total of 171° $(|-53| + 88 + 30)$. The optimum spacing of the asymptotes is 180°. Then, any plane (resulting in any desired parking orbit inclination) can be placed through these asymptotes with both an in-plane deboost and transearth injection. This is described in detail in Reference 6 and Reference 7.

In Figures 2 through 5 it is possible to see one other phenomenon which places the translunar and transearth v-infinity asymptotes on opposite sides of the equator. This is because the limiting accessibility days occur when the translunar v-infinity asymptote is as far from the equator as possible, which means the nodes of the earth-moon plane and the moon's equator will be 90° on either side of this point. The moon will rotate about 30° during the lunar stay, which will place the node (nearest the landing region) at selenographic longitudes ranging from -30° to $+30^{\circ}$. The transearth v-infinity lies at selenographic longitudes from 60 to 90°. Thus, it is apparent from having passed through the node to reach the transearth v-infinity asymptote, that it must be on the opposite side of the equator from the translunar v-infinity asymptote. These geometrical variations illustrate the fact that the minimum propellant region on the limiting days will generally be skewed. Furthermore the "optimum" longitude (i. e., that longitude which provides the maximum range of latitude covered) will generally lie to the east of the zero meridian, although it will also be skewed in the north-south direction by the same 6° or 7° amount.

It is thus possible to guess at the limiting days in a lunar month based only on geometrical considerations at the moon. The librations of the moon provide an easy starting point. For the western landing area, it is best to choose the longest possible translunar flight time (95 hours), which will place the translunar v-infinity asymptote at longitudes ranging from -62° to -78° depending on the lunar distance. Figure 6 shows typical longitudes for various combinations of flight time and lunar distance. For the limiting days the latitude of the arrival asymptote of v-infinity should be about 6.7° above or below the equator. This means the node of the earth-moon plane and the moon's equator at the time of perifocal passage must be 12° to 28° east longitude or from -152° to -168° west longitude, depending on whether the day is limiting for Quadrant 2 (the latter case) or Quadrant 3 (the former case). Choosing the limiting days in this manner will allow finding trajectories which are in the earth-moon plane, yet, as far from the lunar equator as possible. By knowing the declination of the moon and whether the moon is ascending or descending it is possible to choose the proper length of coast and the injection ocean (Atlantic or Pacific) for trajectories which are in the earth-moon plane. When intercepting the moon while it is descending, the Pacific Ocean injection provides in-plane trajectories, whereas when intercepting the ascending moon the Atlantic Ocean injections provide in-plane trajectories.

In choosing launch dates which are limiting for eastern landing sites the translunar trajectory can be similarly chosen because of the symmetry about the earth-moon plane. Quadrant 1 launches will be similar to Quadrant 3 and those in Quadrant 4 to Quadrant 2. Or conversely, the translunar v-infinity asymptote will be limiting to the opposite quadrant on the same side of the lunar equator. Thus positive latitude asymptote (piercing Quadrant 2) limit Quadrant 1 and negative asymptotes (piercing Quadrant 3) limit Quadrant 4. Maximum accessibility in the eastern longitudes is achieved by maximizing transearth flight time. This means choosing the longest possible transearth flight time (110 hours), coupled with the appropriate translunar time will give maximum accessibility in the limiting quadrant. The appropriate translunar flight time is not necessarily the longest possible. In fact, this flight time has proven to be remarkably short. Choosing the transearth flight time fixes the time of departure, and this in turn fixes the time of arrival for a fixed time of lunar operations. For example, this arrival time might require a 109-hour translunar flight time launched on Day 1, but an 85-hour flight time launched on

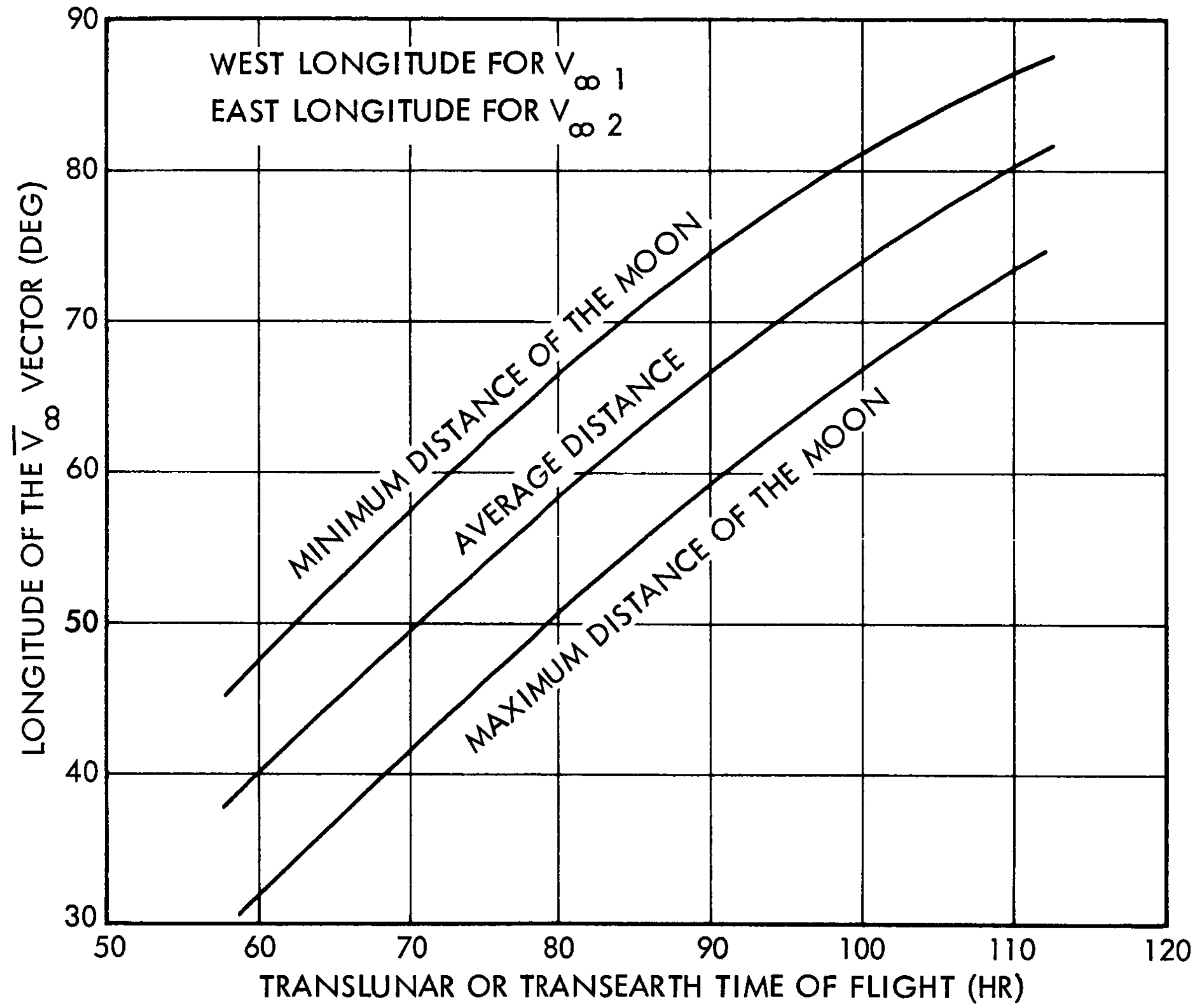

Figure 6. Longitudes of the $\overline{V}_\infty$ Vectors for Various Translunar and Transearth Flight Times

Day 2 arrives at the moon at the same time, or a 61-hour flight launched on Day 3 also arrives at the same time. For eastern longitude landing sites the 61-hour flight time would provide maximum accessibility, in that it moves the "optimum" longitude closer to the transearth v-infinity asymptote. This may severely encroach on the site accessibility in other quadrants, but it is of no consequence to the limiting quadrant. Figures 2 and 5 show this compression due to the large deboost velocity increment required. The compressed landing area is most noticeable near the translunar v-infinity asymptote in the western longitudes. In Figure 5 the SM limit almost bounds the entire southern edge of the landing area.

One further item worth noting is the time-of-flight combination for the limiting day in Quadrant 3, which is shown in Figure 4. This day has a translunar time of 92.5 hours coupled with a 110-hour transearth trajectory. By the general rules which were discussed above, a 95-hour translunar time would be predicted, which would result in a 107.5-hour transearth trajectory. However, on this day, these flight time combinations result in v-infinity asymptotes which are more than 180° apart. The 95.2/110 combination is closer to the 180° value which also provides greater accessibility in the quadrant of interest and for the balance of the lunar landing area.

3.2 LUNAR LANDING AREA ΔV CONTOURS

The limiting days which were determined in the previous section have SM velocity increments associated with each site investigated. These can be plotted as ΔV contours, where a ΔV contour is defined as a line indicating the lunar area accessible for a given velocity increment. This velocity increment will be shown for both deboost into lunar parking orbit (ΔV_1) and at transearth injection (ΔV_2). The ΔV_1 velocity contours for the four limiting days are shown in Figures 7 through 10 for the entire landing area. Similar representations are shown for the ΔV_2 velocity contours in Figures 11 through 14.

Figure 7 shows the ΔV_1 contour for a 1 February 1970 launch with a translunar flight time of 65.5 hours. This launch date is limiting for Quadrant 1, which is the upper right hand area. Several phenomena can be described. The first is the shape of the contours which are generally like those of the SM propellant contours, or the LEM plane change contours presented in the previous section. Where these curves fold back is the point where all of the SM propellant is being expended, and the off-loading of SM propellant for LEM propellant is begun to give the LEM added plane change capability. This is especially noticeable in the upper right of Quadrant 1. This figure can be compared with the LEM plane change contour (Figure 8) which showed maximum site accessibility for this launch date. It can be seen that the 0.5° LEM plane change lies above the fold in the ΔV contours, which indicates that the LEM is being used to relieve the SM velocity requirements sometime before a full 0.5° LEM plane change is needed. Also, the dashed lines in Figure 7 show the minimum ΔV contour. In addition, the point where the maximum ΔV occurs is indicated (*). Maximum ΔV does not have a constant value like the minimum ΔV. The minimum follows a line which is symmetrical about the v-infinity positions and travels toward the poles near the "optimum" longitude. The SM limits bound the area and indicate maximum spacecraft capability within the LEM plane change/SM propellant trade-off. No further compromises in loading can be made to increase the accessibility at this point without an increase in the injected weight.

LIMITING LAUNCH DAY FOR QUADRANT 1
TF1 = 65.5 HOURS   TF2 = 110 HOURS

MAXIMUM ΔV_1 = 3,415 FT/SEC

MINIMUM ΔV_1 = 3,085 FT/SEC

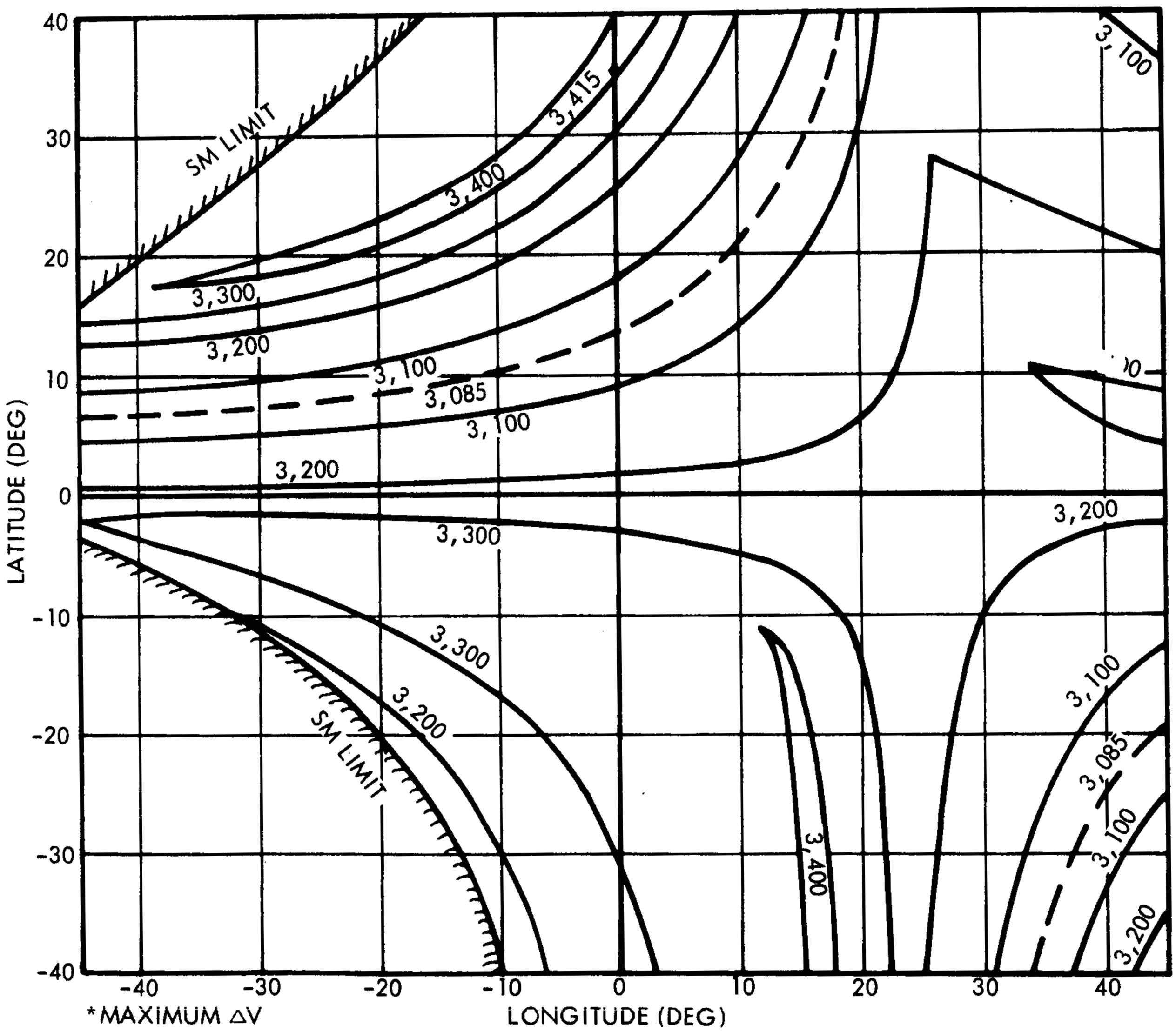

Figure 7. SM Deboost Velocity (ΔV_1) Contour for 1 February 1970

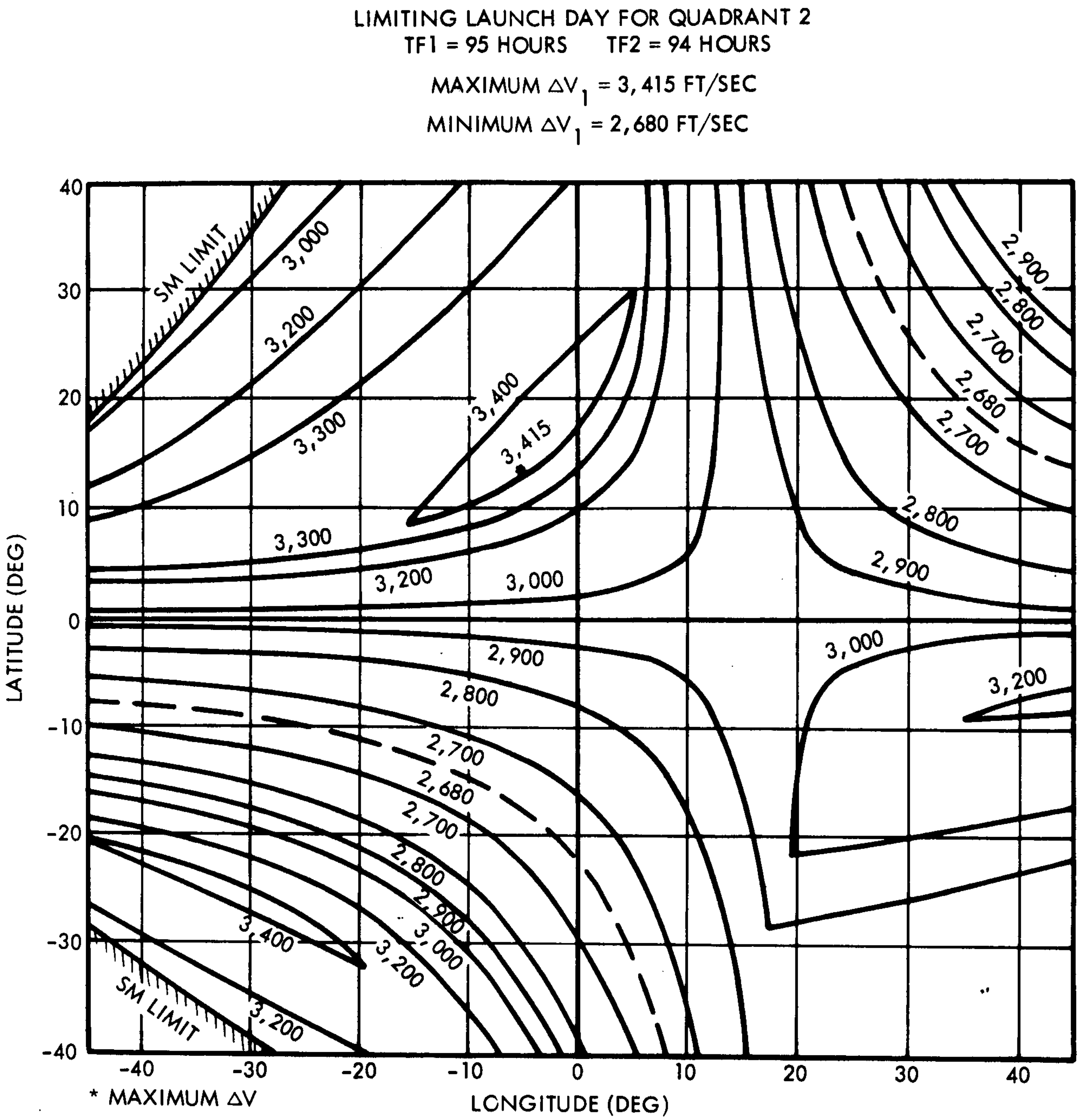

Figure 8. SM Deboost Velocity (ΔV_1) Contour for 15 February 1970

LIMITING LAUNCH DAY FOR QUADRANT 3
TF1 = 92.5 HOURS   TF2 = 110 HOURS

MAXIMUM ΔV_1 = 3,435 FT/SEC

MINIMUM ΔV_1 = 2,714 FT/SEC

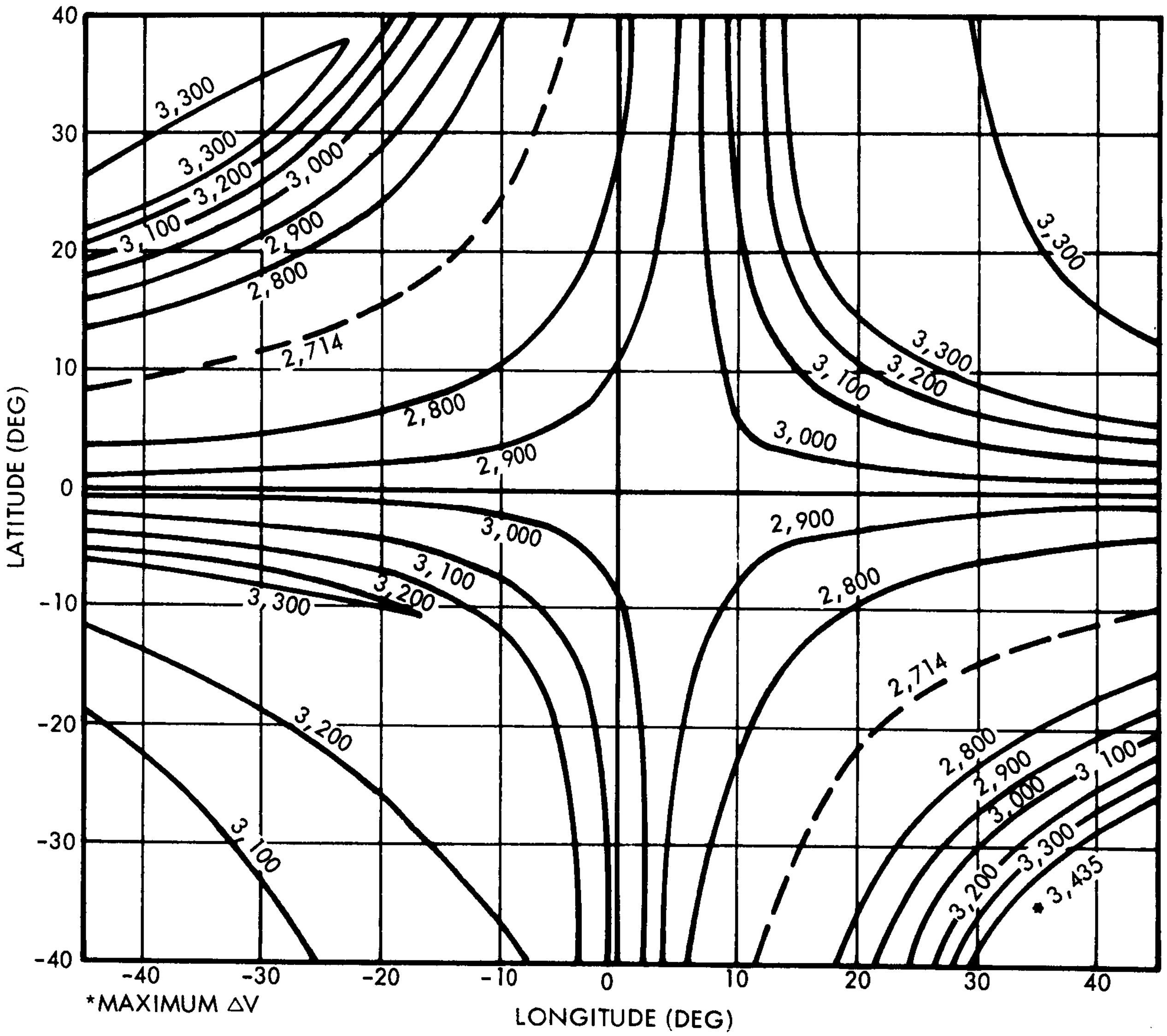

Figure 9. SM Deboost Velocity (ΔV_1) Contour for 4 February 1970

LIMITING LAUNCH DAY FOR QUADRANT 4
TF1 = 80 HOURS TF2 = 110 HOURS
MAXIMUM ΔV_1 = 3,470 FT/SEC
MINIMUM ΔV_1 = 2,855 FT/SEC

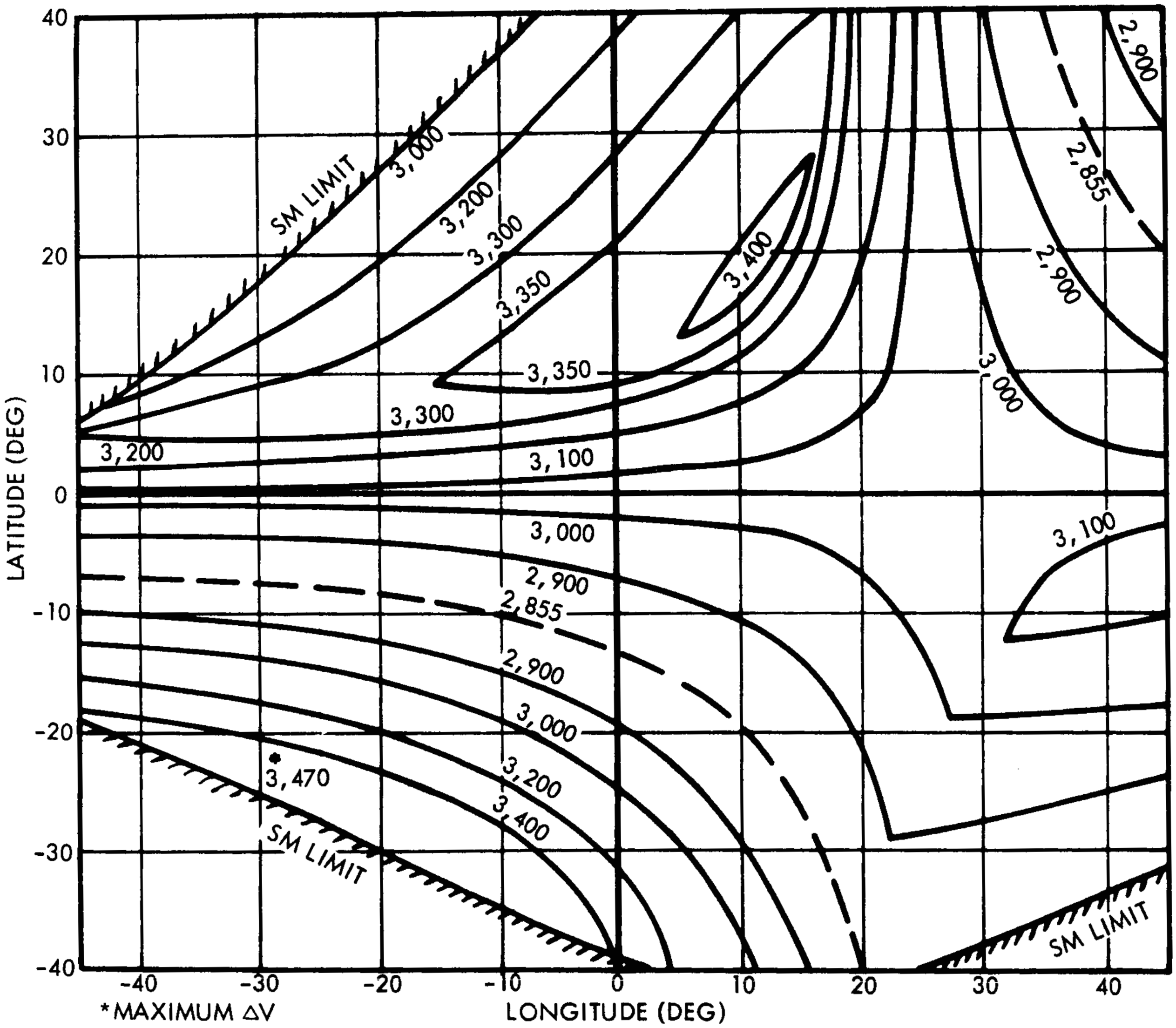

Figure 10. SM Deboost Velocity (ΔV_1) Contour for 17 February 1970

LIMITING LAUNCH DAY FOR QUADRANT 1
TF1 = 65.5 HOURS TF2 = 110 HOURS
MAXIMUM ΔV_2 = 3,265 FT/SEC
MINIMUM ΔV_2 = 2,715 FT/SEC

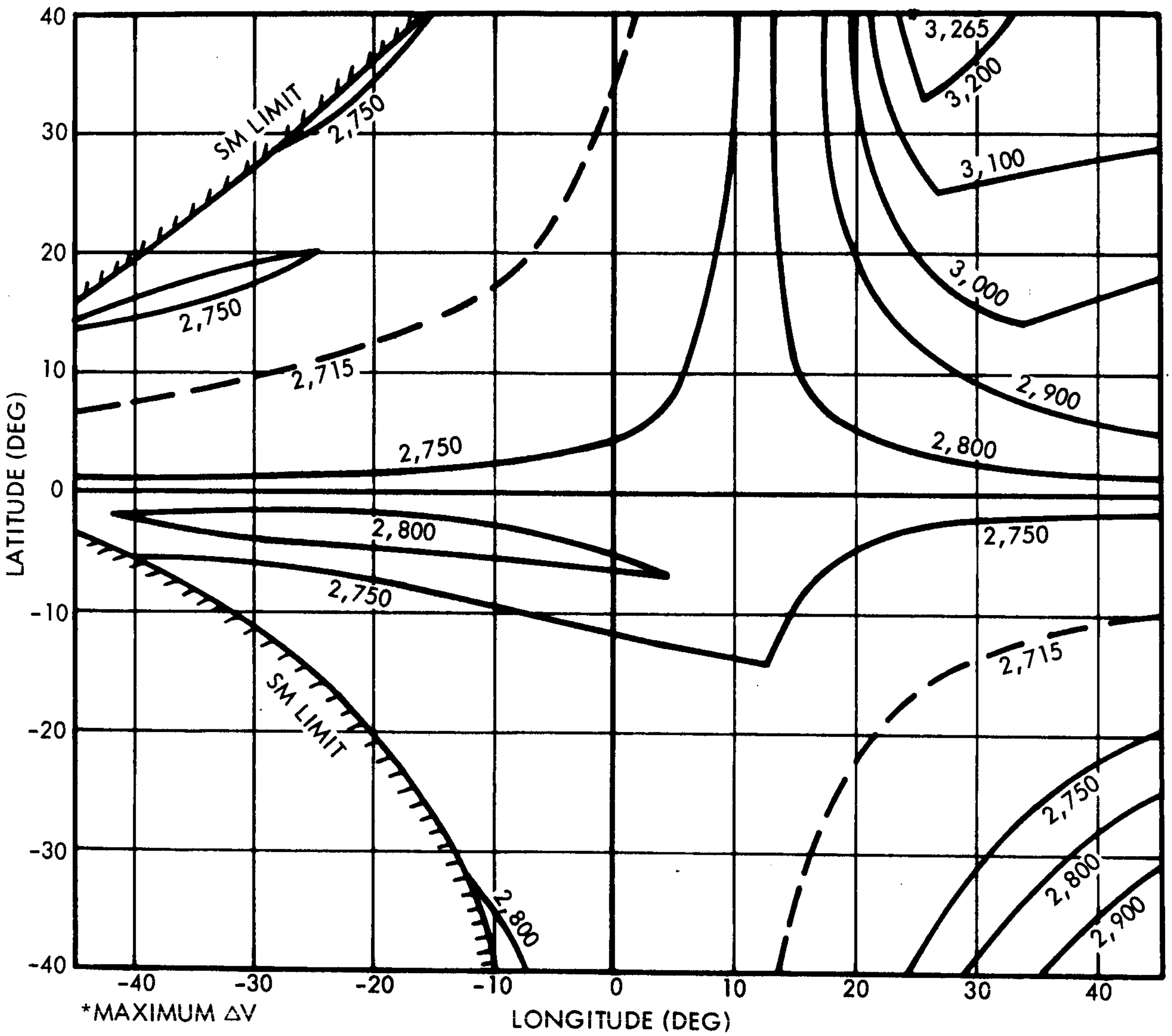

Figure 11. SM Return Injection Velocity (ΔV_2) Contour for 1 February 1970

LIMITING LAUNCH DAY FOR QUADRANT 2
TF1 = 95 HOURS   TF2 = 94 HOURS

MAXIMUM ΔV_2 = 4,000 FT/SEC

MINIMUM ΔV_2 = 2,698 FT/SEC

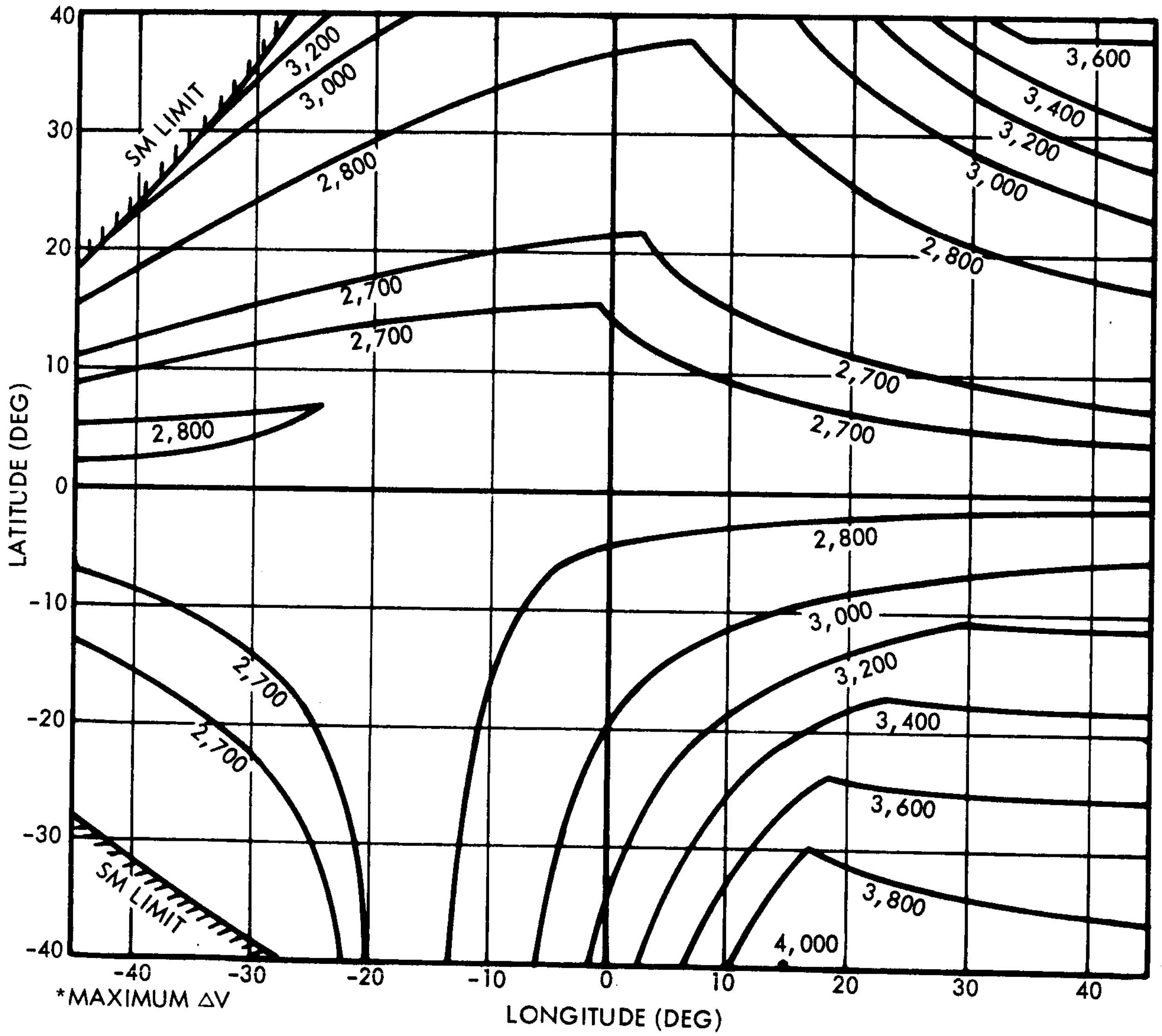

Figure 12. SM Return Injection Velocity (ΔV_2) Contour for 15 February 1970

LIMITING LAUNCH DAY FOR QUADRANT 3
TF1 = 92.5 HOURS TF2 = 110 HOURS

MAXIMUM ΔV_2 = 3,215 FT/SEC
MINIMUM ΔV_2 = 2,670 FT/SEC

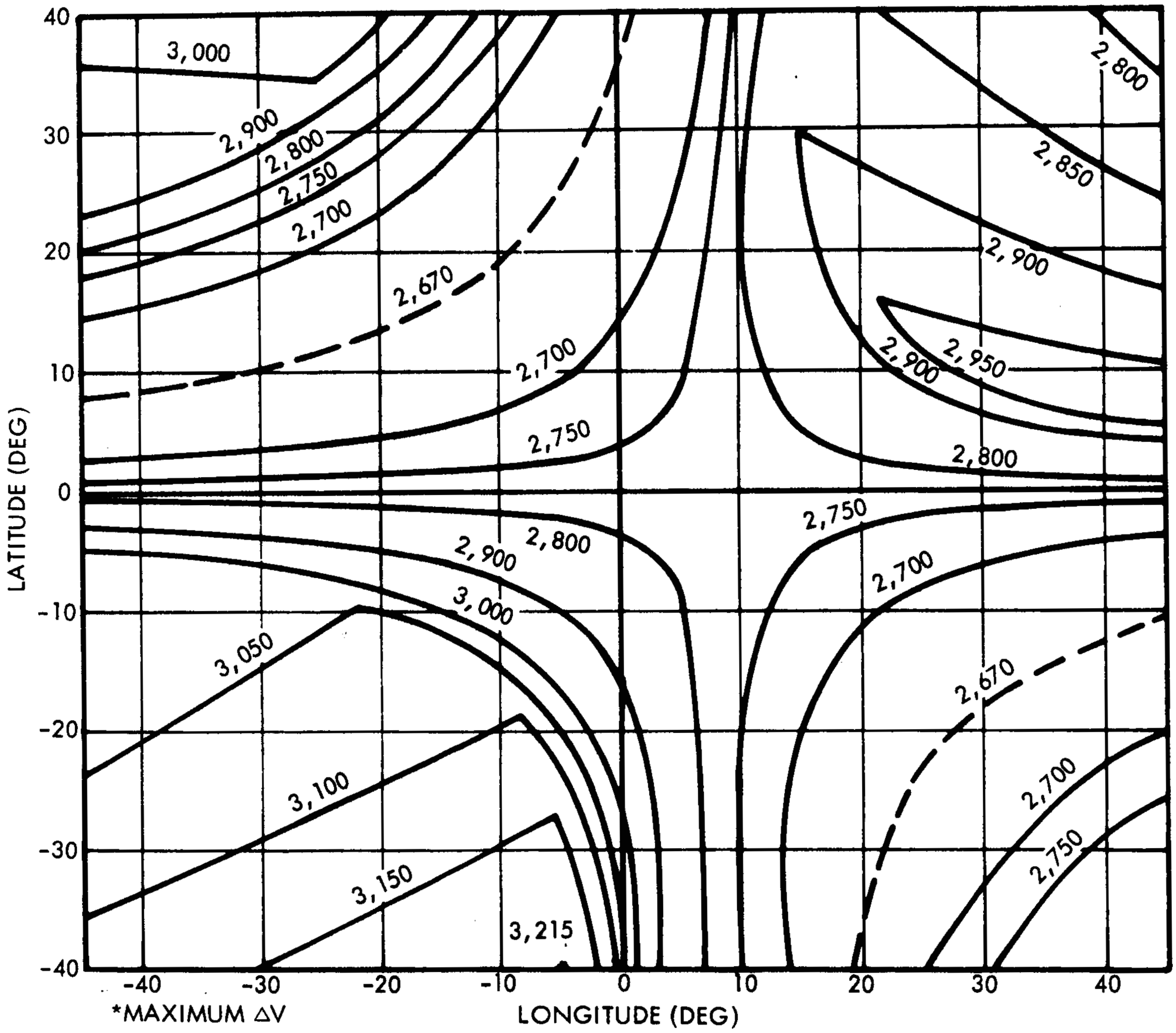

Figure 13. SM Return Injection Velocity (ΔV_2) Contour for 4 February 1970

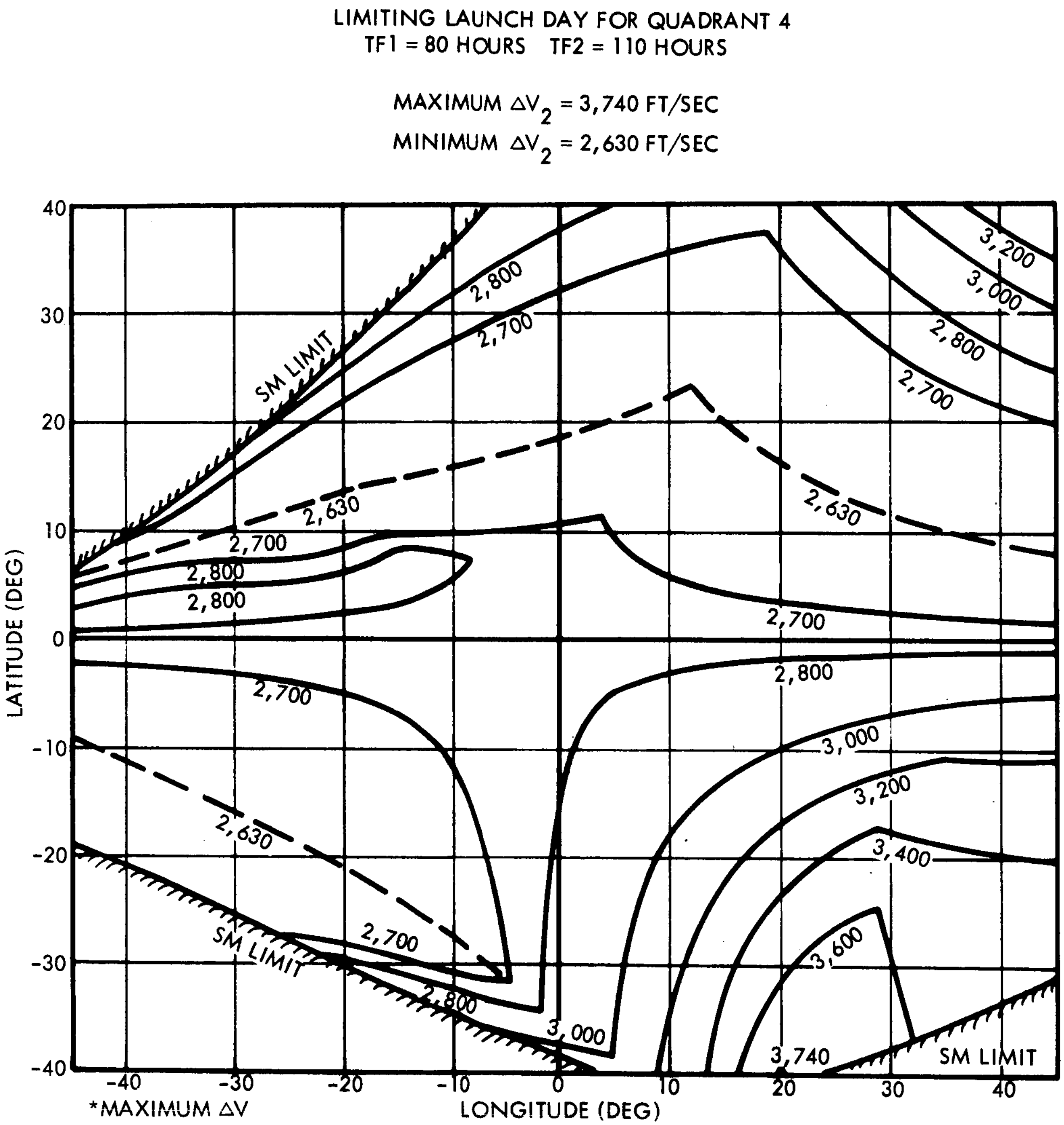

Figure 14. SM Return Injection Velocity (ΔV_2) Contour for 17 February 1970

The velocity increment contours for the remaining days are consistent with those described for the 1 February 1970. A summary of the velocity increments is given in Table 4, which presents the minimum and maximum values of the increments to be expected. These are shown both for the entire range of the landing area (±40^o latitude) and the Apollo landing area (±5^o latitude). The ΔV's in the Apollo landing area naturally have the smaller range of values. Delta V_1 has a range of approximately 420 ft/sec during the month, while ΔV_2 varies by 285 ft/sec. This difference is due in part to the flight times required; the translunar flight time ranges from 65 to 95 hours but the transearch only ranges from 94 to 110. The velocity requirements change very little at the long flight times. The launch date of 15 February (Quadrant 2) provides both the maximum ΔV_1 with a 95-hour translunar flight time and the minimum ΔV_2 at a 94-hour flight time. Quadrant 3 (launch on 4 February) provides the maximum ΔV_2 with a 110-hour return, while the minimum ΔV_1 occurs in Quadrant 4 for a 17 February launch at an 80-hour translunar flight time.

The difficulty in relating the velocity increments to the expected values on the limiting days stems from several contradictory factors. The first is the influence of the lunar distance, which for example, on the limiting days in Quadrants 1 and 3 when the moon is near its perigee, will in general reduce the moon phase velocity. However, in Quadrant 1 the translunar flight time is short (65 hours), which increases moon phase velocity. But, the limiting quadrant is quite far removed from the translunar v-infinity asymptote and near the optimum longitude, which tends to reduce ΔV_1 (although the average value is still higher than the other days). The latitude/longitude positions of both the translunar and transearth v-infinity asymptotes are the prime determinants of the limiting days. The effects of these were discussed in the previous section. The relative asymptote positions, the lunar distance, the flight times chosen, and the landing area considered, all interact to provide a complex pattern of velocity requirements. Also recall that in these cases the strategy used in developing the contours was to minimize LEM plane change required. This requires most of the maneuvers to be executed by the SM, which then does not provide minimum propellant expenditures or minimum ΔV expenditures. Thus, the magnitude of these numbers are conservatively high, although the proportions between the days should be similar.

Table 4. Range of ΔV Required in Limiting Quadrants

$\pm 40^{\circ}$ Latitude Bound

Limiting Quadrant	Minimum ΔV_1	Maximum ΔV_1	Minimum ΔV_2	Maximum ΔV_2
1	3085	3415	2715	3265
2	2950	3415	2698	3250
3	2960	3315	2775	3215
4	2855	3370	2765	3740

$\pm 5^{\circ}$ Latitude Bound

Limiting Quadrant	Minimum ΔV_1	Maximum ΔV_1	Minimum ΔV_2	Maximum ΔV_2
1	3145	3315	2748	2890
2	3950	3355**	2730*	2875
3	2960	3295	2775	3015**
4	2833*	3143	2780	3000

*Minimum ΔV

**Maximum ΔV

3.3 ΔV CONTOURS FOR FIXED LEM WEIGHT

The strategy to optimize lunar site accessibility requires that the LEM plane change be kept to a minimum for as long as possible by first utilizing the SM to make as much of the plane change as possible within the propulsion limits. The only time the LEM is then called upon to make more than the minimum plane change is when all of the SM propellant is expended and off-loading in favor of the LEM begins. This strategy is represented in the contours presented in Section 3.1.

In this analysis, Section 3.3, the strategy is to minimize the SM propellant expended. The ground rules are also modified slightly. The LEM will have a fixed weight of 32,000 pounds with up to a 2° ascent plane change capability. The approach here will be to fully load the SM (within the spacecraft injected weight capability) and to determine the orbit which provides minimum expenditure of SM propellant.

The landing area to be investigated is designated the "Apollo landing area" and is bounded by $\pm 45^{\circ}$ longitude and $\pm 5^{\circ}$ latitude. The days investigated will be each day of the month in February. The flight times will be optimized for the landing region. The analysis in this section is handled in the LOP program much the same way as the previous analysis, except the test is SM propellant instead of LEM plane change. The azimuth of the orbit passing over the site which provides minimum LEM plane change is the starting point, and the SM propellant is determined for this. The azimuth is advanced/or decreased by 2° increments in the direction of decreasing SM propellant. When the minimum SM propellant is passed or when the value begins to increase after decreasing, the azimuth is backed up 1° and the SM propellant determined. The three points which are determined last are then fit parabolically to determine the minimum. This azimuth is then used to calculate the final values. This holds if the LEM plane changes does not exceed 2° in this range of azimuths. If the LEM plane change limit is exceeded, the plane change is fit to the limit, and the propellant weight is calculated at this azimuth. Both the LEM plane change and the SM propellant are tested simultaneously in finding the best azimuth (orbit inclination) for the landing site.

Each day in the month of February was investigated for minimum propellant requirements in the Apollo landing area. Data obtained for each day plotted on the automatic plotter as contours of minimum SM propellant, ΔV_1, the deboost velocity increment, and ΔV_2, the transearth injection velocity increment. Representative contours for specific days will be included in this report. Data from all of the days in the month can be summarized in three graphs. In Figure 15 the range of values of SM propellant in the Apollo landing area for launches during the entire month of February 1970 is given. The solid lines represent the range at a -45° longitude and the dashed lines at a $+45^{\circ}$ longitude. At the -45° longitude a 95-hour translunar flight time gives the minimum SM propellant expenditures. The maximum variation at -45° is 2,000 pounds, which occurs when the moon is at apogee near 16 February. The latitude librations are also maximum at this time and two of the limiting days (15 and 17 February) also occur in this period. The other peak is near 3 February, when the moon is at perigee and the latitude librations are again maximum. The other 2 limiting days, 1 and 4 February, were found in this period.

The range of SM propellant experiences a less severe variation at $+45^{\circ}$ longitude, because it is nearer the "optimum" longitude in all cases and not much compression of the accessibility is evident. For launches from 1 through 8 February, the minimum SM propellant at eastern longitudes is necessary with a maximum transearth trip time of 110 hours. However on 9 February the transearth trip time begins to exceed the 110-hour limit (for a 95-hour translunar) and consequently the spacecraft must return to earth a day earlier with an 86.5-hour flight time. Also, if the transearth time is held to 110 hours, the translunar trajectory begins to exceed the 95-hour limit, which requires launching from earth one day later with a 72-hour flight time. These effects account for the sharp jump in the minimum values between 8 and 9 February. On 9 February the minimum SM propellant expenditure at $+45^{\circ}$ longitude now results from the 95-hour translunar flight time coupled with a return trajectory which is only 87. 5 hours in duration. The alternative is a 110-hour transearth coupled with a 73. 6-hour translunar. There is an approximate reduction of 400 pounds in SM propellant by going to a 95-hour translunar. This 95-hour flight time holds for the rest of the month in this relatively narrow Apollo landing area. The only

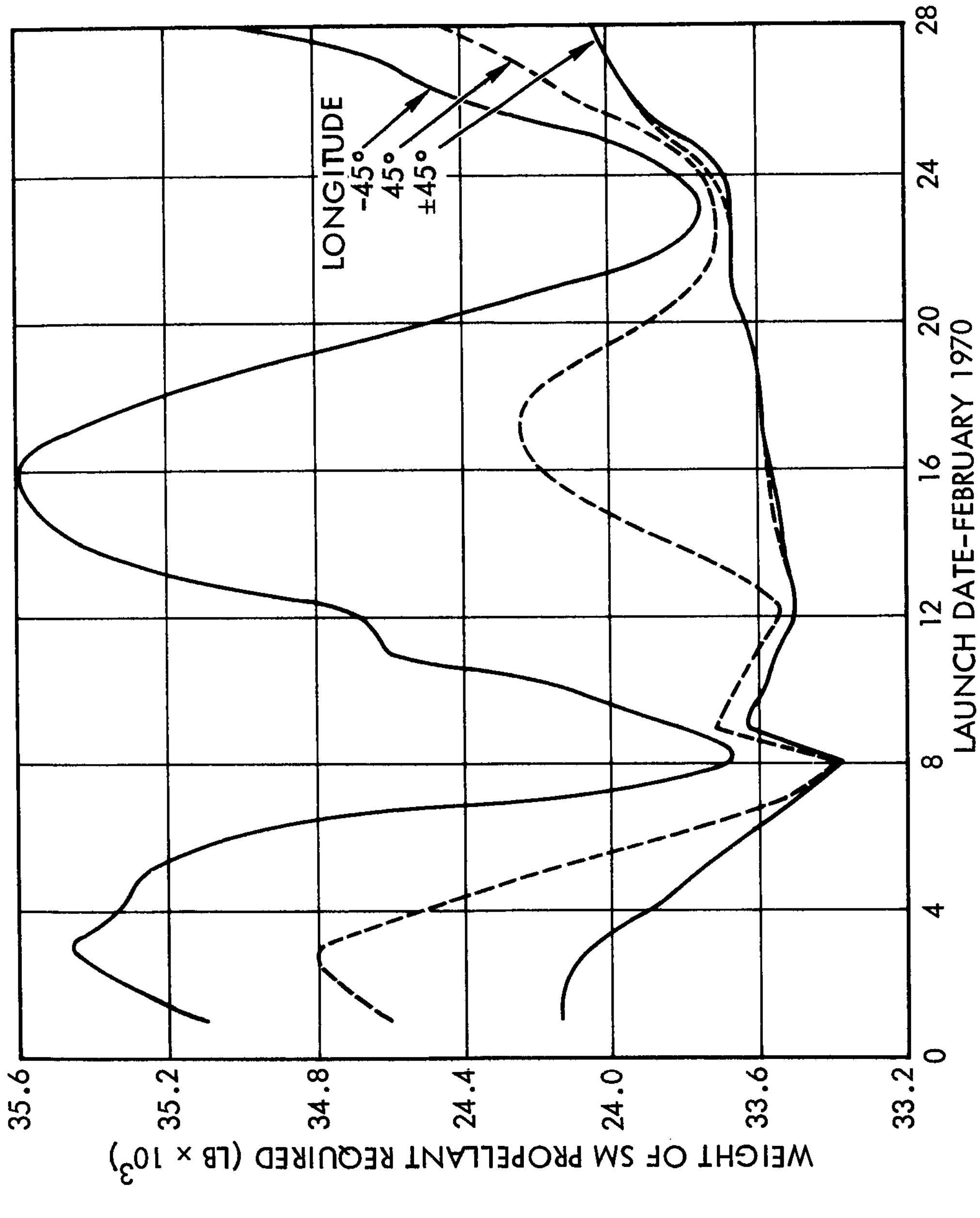

Figure 15. Range of Minimum SM Propellant Required to Reach All Sites in the Apollo Landing Area for Launches in February 1970

time a 110-hour transearth flight time is favorable is on 17 February although it is still shy by 95 pounds of the maximum, and 400 pounds of the minimum required. For launches on 28 February the 110-hour transearth is beginning to look better, mainly because the transearth trajectory is nearing its 95-hour limit again.

Although only the longitudes at $\pm 45^{\circ}$ are shown, these results bracket all of the other longitudes. Figures 16 through 19 for launches on 3, 12, 16, and 20 February illustrate what the typical variations of SM propellant in the landing area are like. These are contours of minimum SM propellant plotted on a selenographic latitude-longitude scale. The latitude scale is expanded by a factor of five over the longitude scale to better illustrate the contours. Figure 16 has the 110-hour transearth flight time case indicated by dashed lines in the eastern landing area to show the improvement that can be obtained in this region. It is also possible to see that the latitude librations are moving the contours from south to north in comparing the launches on 3 and 12 February.

The range of ΔV_1 and ΔV_2 can be illustrated in a manner similar to the minimum SM propellant. This is done in Figures 20 and 21 where the ΔV range on each day is given for an entire month. The maximum and minimum values are given for longitudes of $\pm 45^{\circ}$. Other longitudes would be between the two. The conditions that apply here are identical to those described for the minimum propellant contour. Note that the ΔV_1 curve is symmetrical, as it is possible to launch a 95-hour translunar trajectory from earth on each day.

The range in ΔV_1 for minimum SM propellant expended is about 500 ft/sec as illustrated in Figure 20 ranging from a low of 2,640 ft/sec. Very few sites in this Apollo landing area require more than 3,000 ft/sec. Although those which do, are in the extreme western landing area. The maximum ΔV_1 occurs when the moon is at maximum distance and the latitude librations are maximum. If the month of February were the target month, the lighting incidence angle during LEM descent would be important. Acceptable launches could begin on 7 February for eastern landing sites and continue through 17 February for sites in the extreme western landing area. This time period encompasses the extremes in ΔV_1 which would indicate that an allowance must be made for the maximum value.

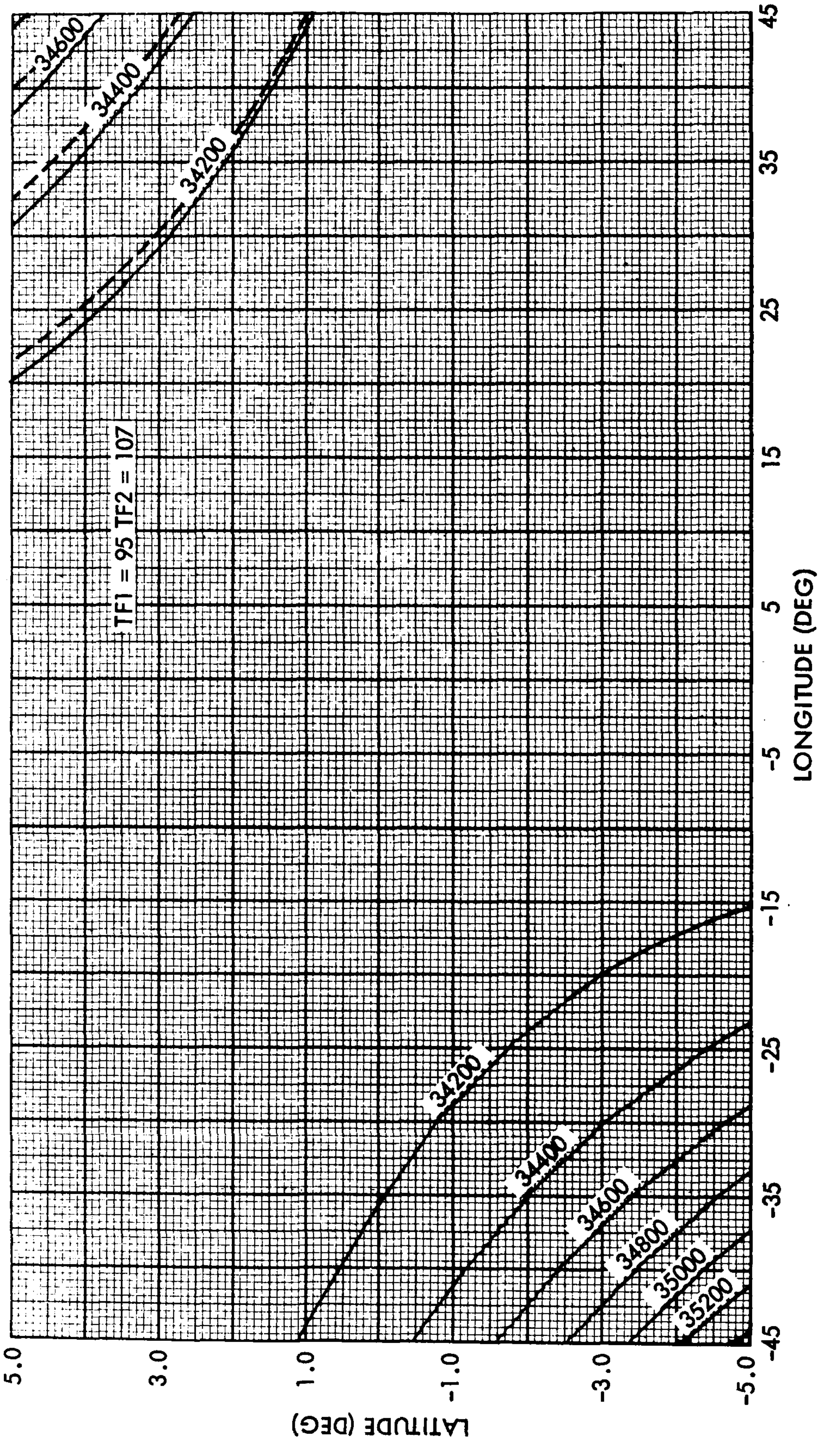

Figure 16. Minimum SM Propellant Launch 3 February 1970

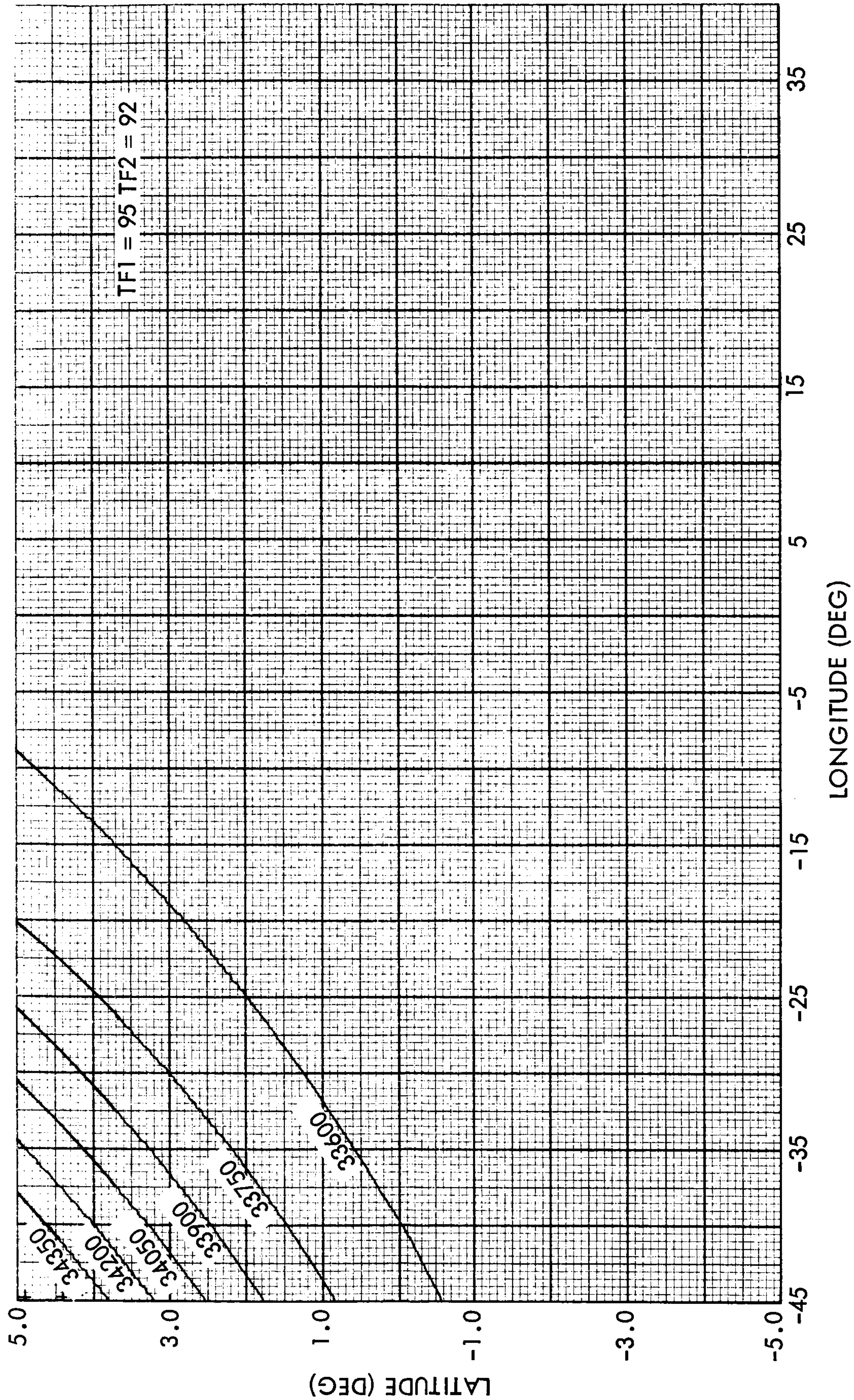

Figure 17. Minimum SM Propellant Launch 12 February 1970

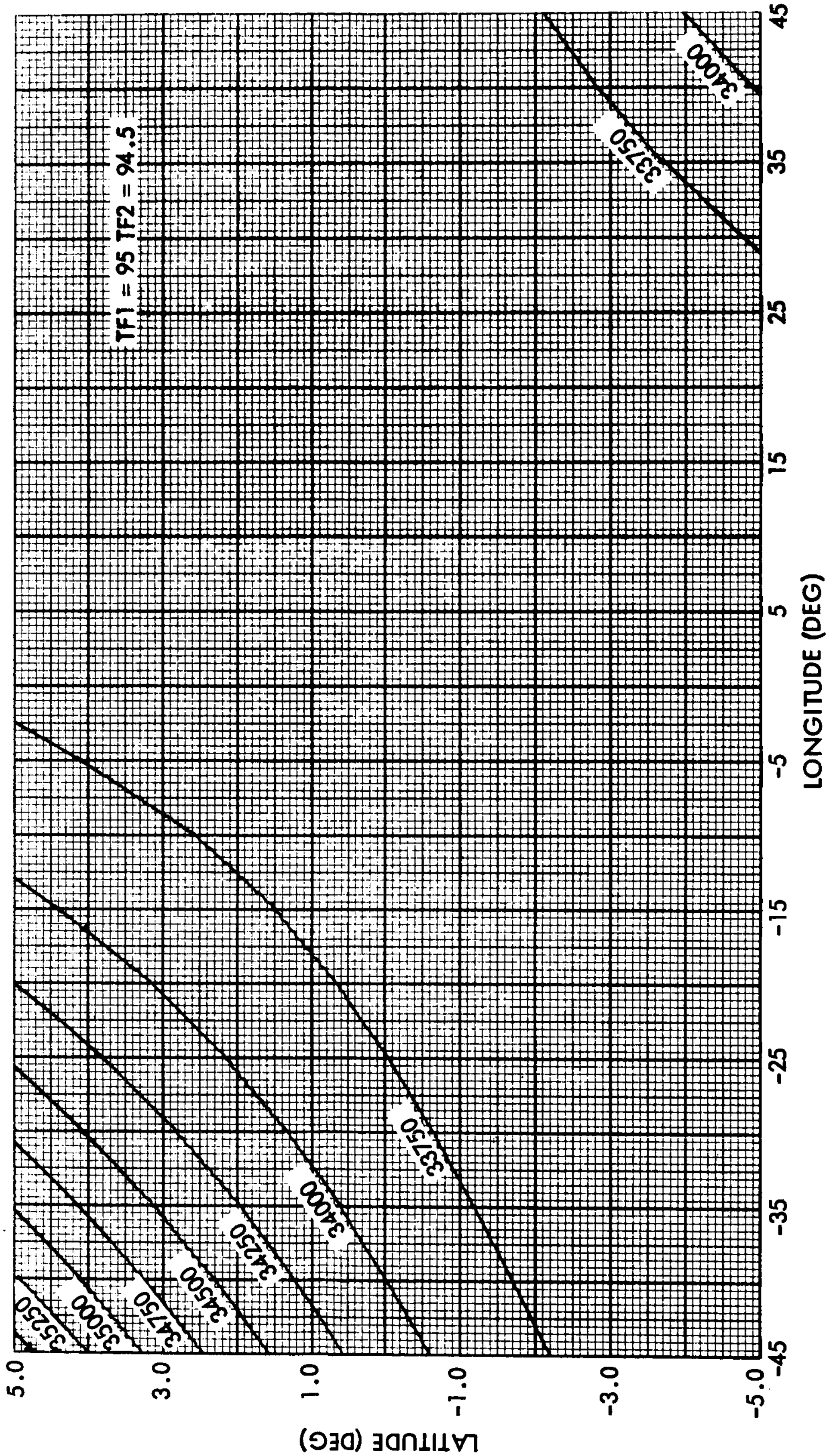

Figure 18. Minimum SM Propellant Launch 16 February 1970

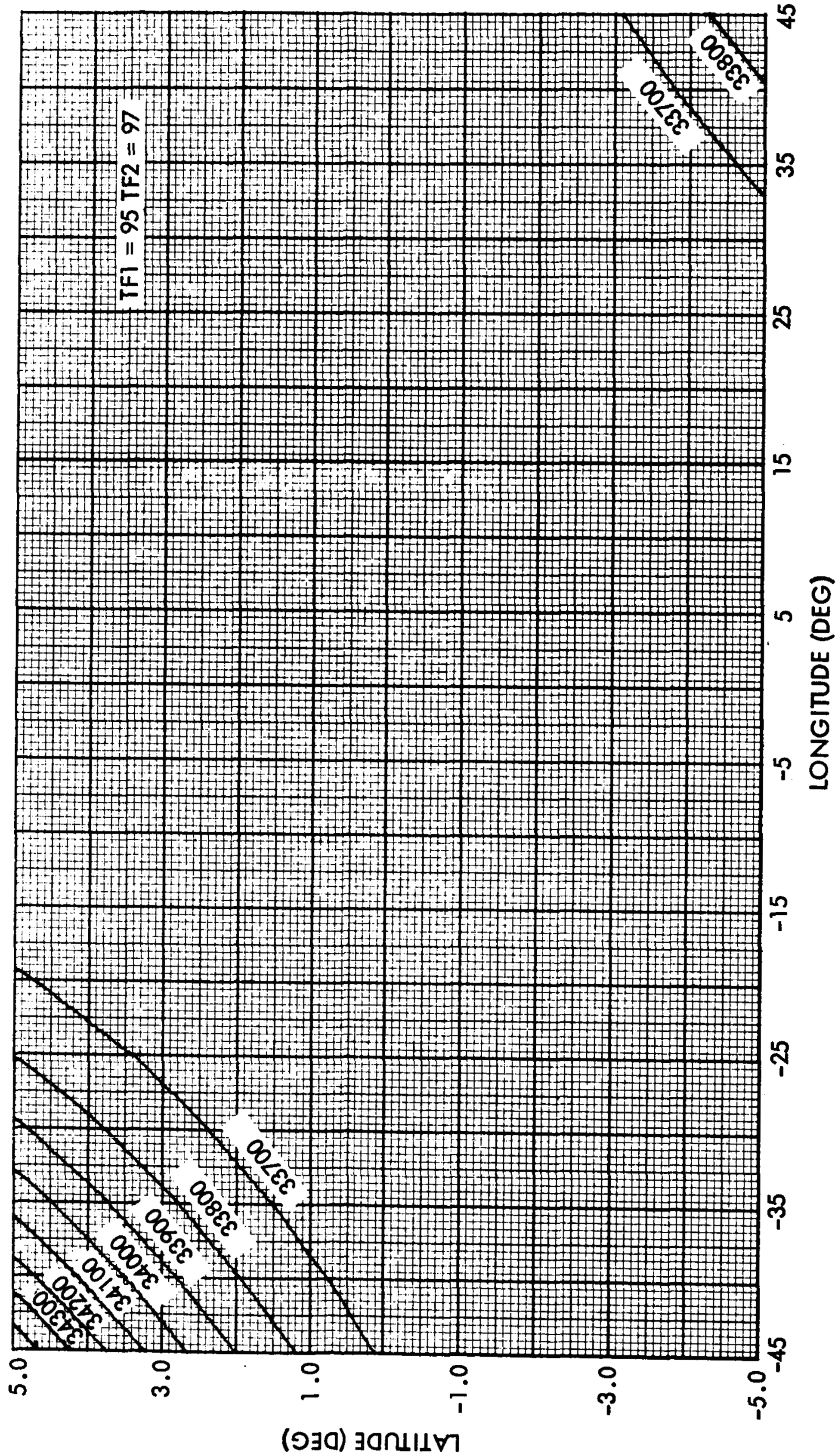

Figure 19. Minimum SM Propellant Launch 20 February 1970

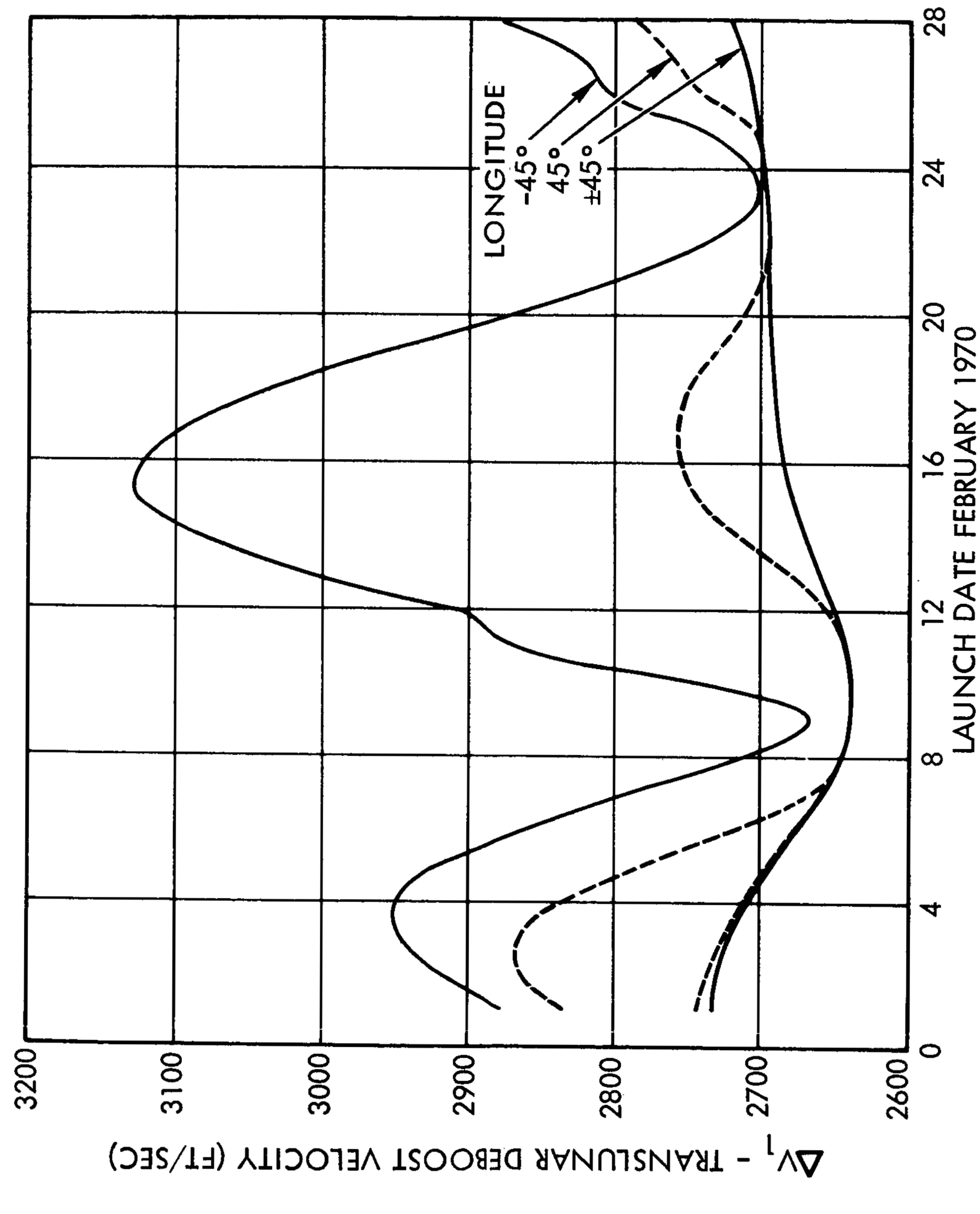

Figure 20. Range of ΔV_1 Required in Apollo Landing Area for February 1970 Launches

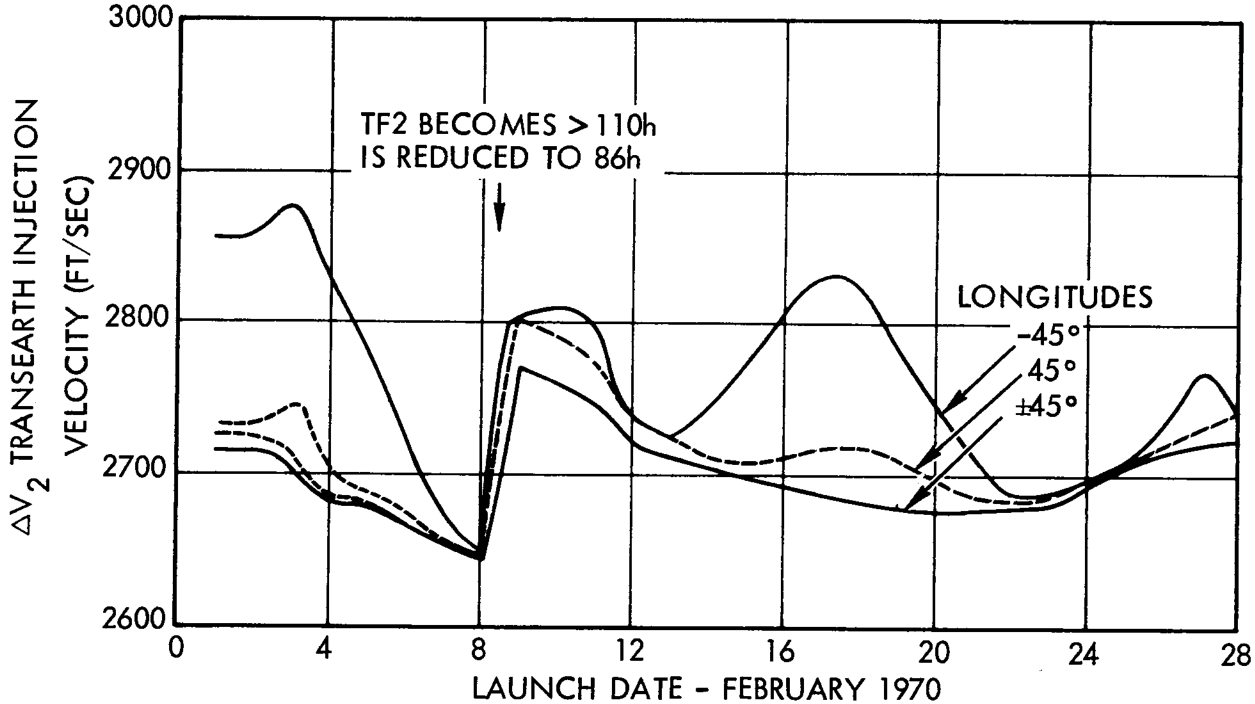

Figure 21. Range of ΔV_2 Required in Apollo Landing Area for February 1970 Launches

The lighting incidence angle has a rapid monthly change and consecutive lunar months would not be too similar in that the relative geometry of the other parameters (i.e., distance, declination, and latitude libration) is changing at a slow rate.

The transearth injection velocity, ΔV_2, experiences a much smaller range (Figure 21) than ΔV_1. This is because it is possible to optimize the return trajectory for each landing site, and the transearth flight time is maintained in the time range from 86 to 110 hours. Also, the locus of the return v-infinity asymptotes, which represent the various return inclinations lies partly in the $\pm 5^{\circ}$ latitude range on every day in the month. This allows in-plane return trajectories to be found most of the time. This was not the case with the deboost maneuver, which may have a v-infinity asymptote outside the $\pm 5^{\circ}$ latitude range requiring deboost plane changes which increase ΔV_1.

The sudden break in the curve (Figure 21) between 8 and 9 February occurs because the transearth flight time begins to exceed 110 hours and on 9 February is dropped to an allowable 86 hours. The range of ΔV_2 is only 230 ft/sec, from a minimum of 2,645 ft/sec to a maximum of 2,875 ft/sec. The large excursions on any day occur at the same launch times as the ΔV_1 and SM propellant. Variations in ΔV_1 and ΔV_2 for various days in the month are included as Figures 22 through 29. These contours are very similar to the SM propellant contours. The values of interpolated arguments result from an automatic interpolation scheme used in the plotter. This method assures an adequate number of contours in the area by specifying the smallest argument increment and the maximum number of increments in the range of the variable. In this manner each plot has its own arguments generated. The latitude scale is also expanded by a factor of five over the longitude scale for clarity.

A brief comparison can be made of strategies in selecting either minimum LEM plane change or minimum SM propellant. Figure 30 shows the SM propellant reserve as a function of the LEM plane change for various lunar landing sites for launches on 15 February 1970. This date was limiting in accessibility in Quadrant 2 and the site of 45, 5 at the western edge of this area is limited to a 0.54° LEM plane change with no SM propellant reserve. Other sites exhibit

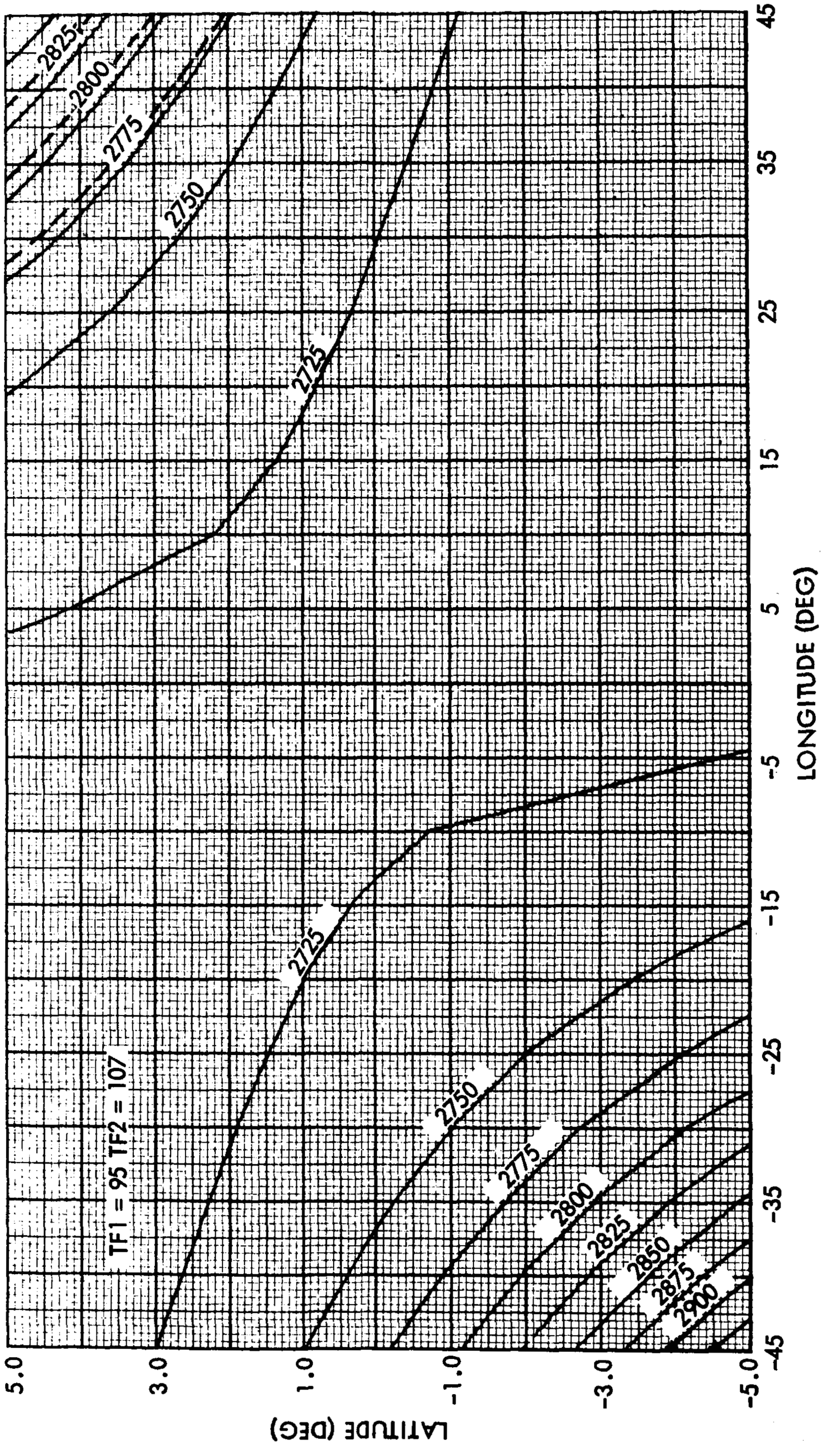

Figure 22. ΔV_1 for Minimum SM Propellant Launch
3 February 1970

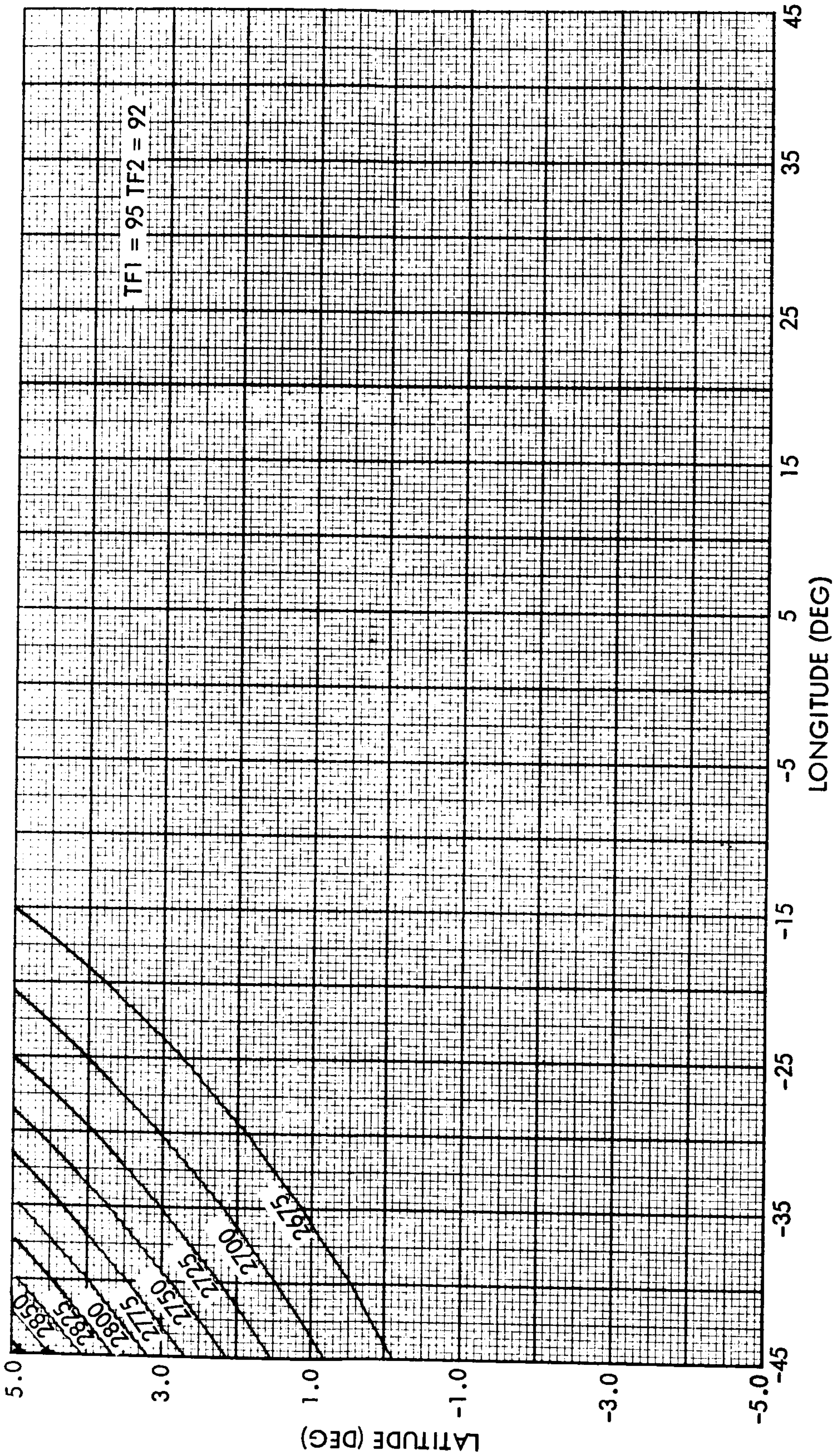

Figure 23. ΔV_1 for Minimum SM Propellant Launch
12 February 1970

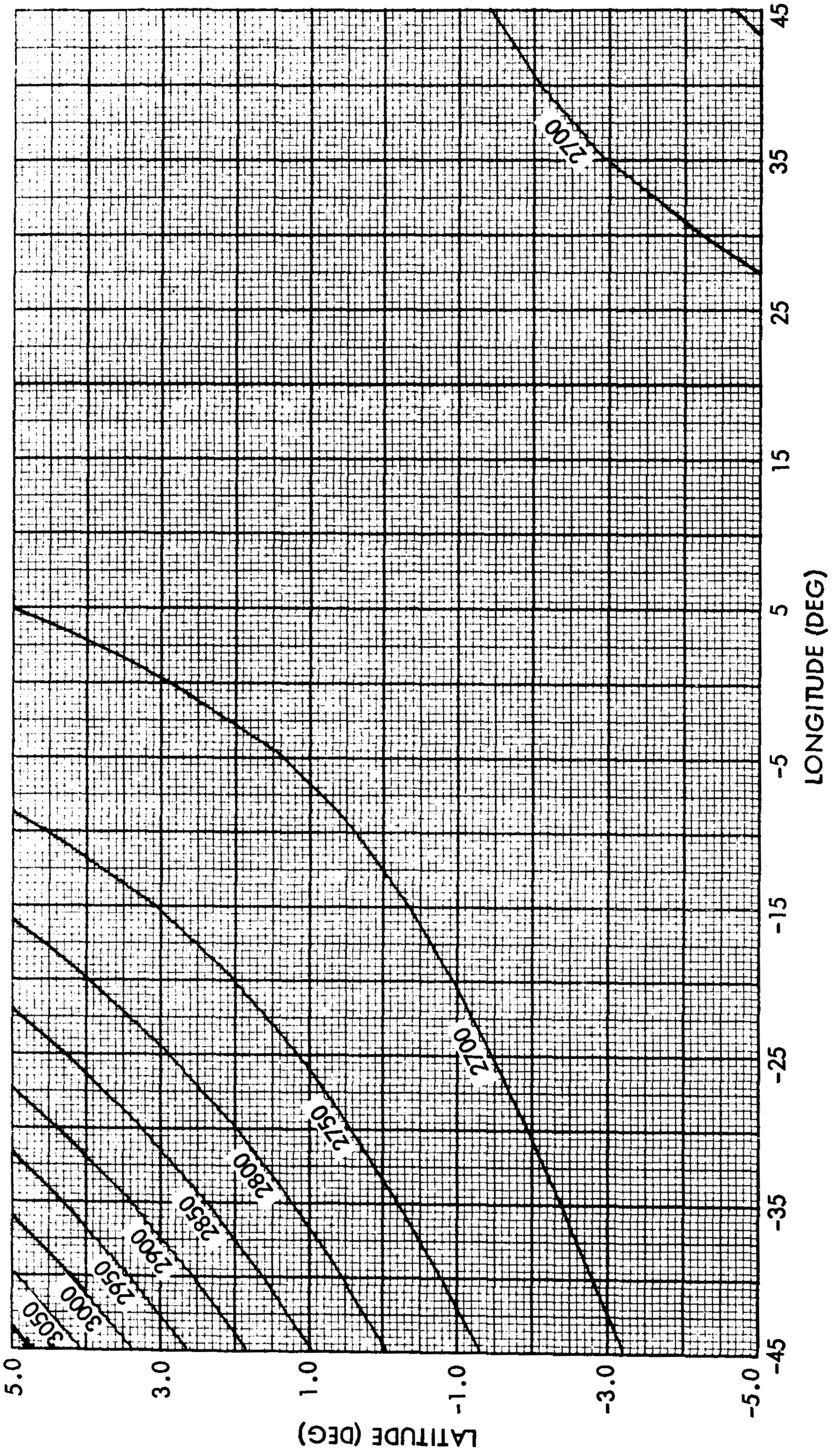

Figure 24. ΔV_1 for Minimum SM Propellant Launch
16 February 1970

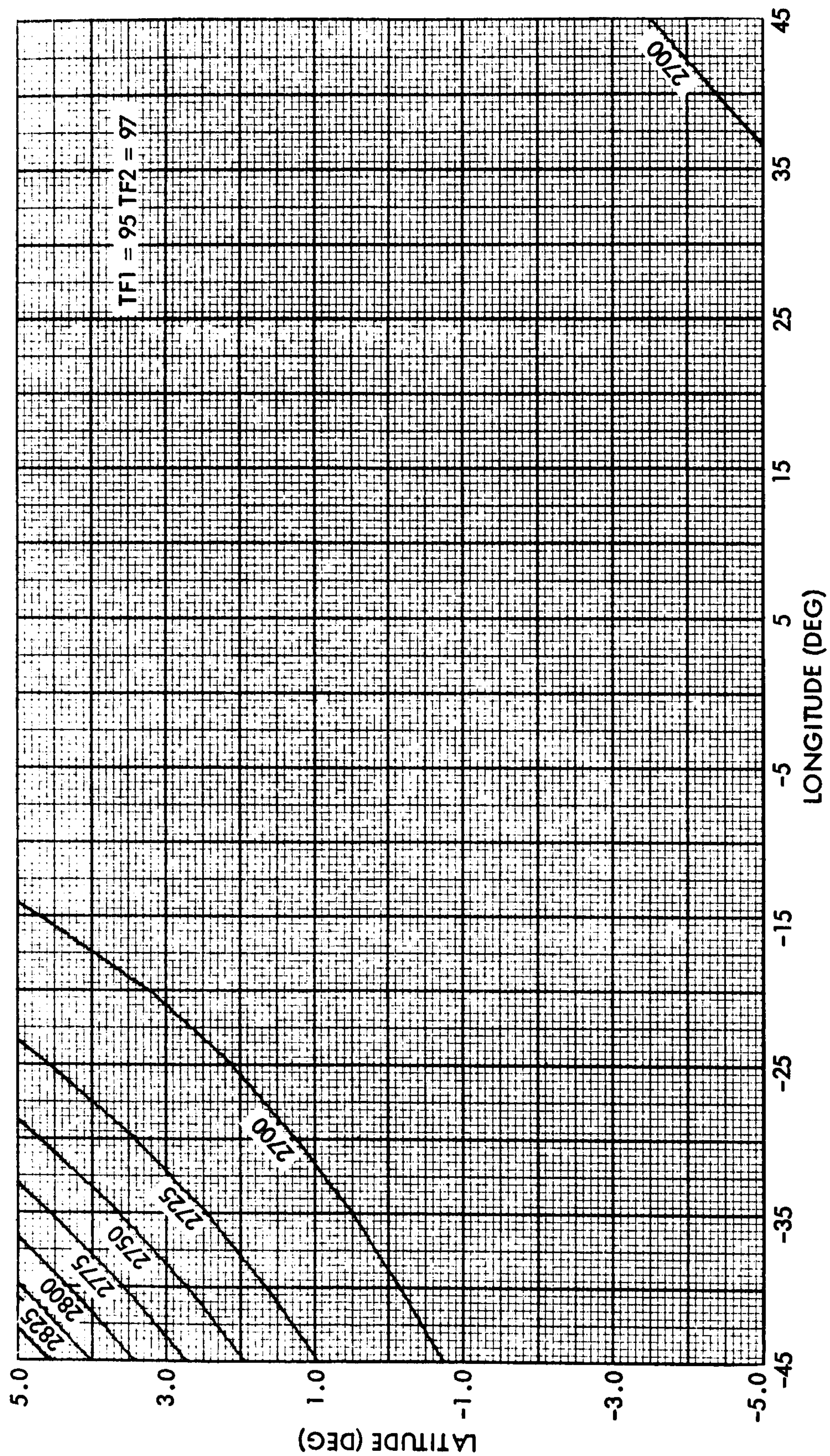

Figure 25. ΔV_1 for Minimum SM Propellant Launch
20 February 1970

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